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HIGH RADAR RANGE RESOLUTION
WITH THE STEP FREQUENCY WAVEFORM

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 1994

REPORT DOCUMENTATION PAGE

Form Approved

OMB No 0704-0188

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE June 1994		3. REPORT TYPE AND DATES COVERED Master's Thesis	
4. TITLE AND SUBTITLE HIGH RADAR RANGE RESOLUTION WITH THE STEP FREQUENCY WAVEFORM				5. FUNDING NUMBERS	
6. AUTHOR(S) Paulose, Abraham Thomas					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the United States Government					
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; Distribution is unlimited				12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) High range resolution can be obtained using a number of methods including ultra-wideband radar, intrapulse pulse compression, and super-resolution techniques. This thesis investigates the achievement of high radar range resolution by means of the step frequency waveform. The key advantage of the step frequency approach compared to other methods is the wide total bandwidth resulting in high range resolution while still maintaining a narrow instantaneous bandwidth which eases A/D sampling requirements. The effects of various waveform parameters on the high resolution range profile are determined for both noise and clutter limited environments. A novel technique is developed which enhances the resolution of moving targets in clutter and estimates the target velocity. This method consists of clutter cancellation followed by successive velocity compensations. Finally, design methods are developed to optimize system performance in a low PRF mode for both noise and clutter limited environments					
14. SUBJECT TERMS Step Frequency Radar, Stepped-Frequency waveform, High Resolution Radar, HRR				15. NUMBER OF PAGES 104	
				16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL		

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I. INTRODUCTION

One important feature of any radar system is the resolution of the target in the range domain. A fine range resolution allows the user to distinguish between two closely spaced targets that might otherwise be incorrectly judged as a single target and can aid in the target identification process. Moreover, a fine range resolution will enhance the target signal relative to the background clutter. For any pulsed radar system, an increase in the effective waveform bandwidth will improve the range resolution.

In recent years, a number of high resolution techniques have been available to the radar designer to improve the range resolution of the radar system. These techniques can be grouped into four main categories: ultra-wideband radar (UWB), superresolution techniques, intrapulse pulse compression techniques, and interpulse pulse compression techniques.

Ultra-Wideband Radar achieves fine range resolution because of the extremely narrow pulses (on the order of nanoseconds) which are transmitted without carrier. As a result, the large instantaneous bandwidth imposes severe constraints on the analog to digital conversion process since the waveform sampling must meet the Nyquist criterion. Moreover, the UWB radar requires new wideband components different from those used in conventional narrowband radars. [Ref. 1:p. 31]

Superresolution techniques involve the use of high-resolution optimal estimation methods. These methods are based on an eigenstructure technique that makes use of the covariance matrix of the received signal [Ref. 2:p. 18].

Intrapulse pulse compression (PC) methods have been commonly used to increase the range resolution of radar systems. These techniques increase the instantaneous bandwidth

by applying either frequency coding or phase coding to each transmitted pulse. The received pulses are processed in a filter matched to the transmitted signal resulting in a compressed pulse. Frequency coding techniques include the common linear frequency modulation (LFM) or chirp method, and discrete coded segments within the pulse [Ref. 3:pp. 420-424]. Phase coding techniques include binary phase codes as well as various polyphase codes [Ref. 4:pp. 223-228].

The step frequency waveform is an interpulse pulse compression method in which the carrier frequency of successive pulses is varied by a fixed frequency step. Wide bandwidth is indirectly achieved over several pulses instead of within a single pulse as in conventional pulse compression signals. The effective waveform bandwidth is the product of the number of coherently integrated pulses N and the frequency step size ΔF .

The returns of these N pulses at different carrier frequencies constitute the frequency spectrum of the target reflectivity and are coherently integrated by the inverse FFT to yield the high resolution range profile (HRR profile). The signal processing transforms wide original range bins into finer range bins. The HRR profile does not give absolute range position of the target but gives the relative position of each scattering center within the original range bin.

The key advantage of the step frequency method compared to other pulse compression techniques is that the range resolution is increased while still maintaining a narrow instantaneous bandwidth. As a result, the analog to digital conversion requirements are less stringent. Moreover, as opposed to the UWB waveform, the range resolution can be achieved by merely adding a stepped frequency synthesizer to a conventional narrowband radar receiver and performing the required signal processing on the received signal.

The step frequency waveform has two primary limitations. First, as opposed to a pulse-doppler radar, the step frequency radar cannot directly measure the velocity of moving targets based on the Doppler shift. Second, as compared to intrapulse pulse compression, the step frequency waveform requires additional time to transmit and receive N pulses needed to obtain the equivalent wide bandwidth of a single narrow pulse.

The purpose of this thesis is to investigate the means by which high range resolution can be achieved via the step frequency waveform. Chapter II presents the primary step frequency radar parameters, a brief system description, and the signal processing that results in the fine range resolution. Chapter III summarizes the relationships between the various radar design parameters and their effects on the overall system performance. Moreover, this chapter presents methods for designing a step frequency radar system based on various user requirements and constraints. Chapter IV presents the results of a high range resolution (HRR) simulation using the step frequency waveform. The simulation output is the processed range profile corresponding to one original range bin. The HRR simulation graphically displays the effect of varying individual radar parameters in both noise-limited and clutter-limited situations. In addition, a new technique is presented which enhances the range resolution of moving targets in clutter and estimates the target velocity by clutter cancellation followed by repeated velocity compensations. Appendix A contains the detailed description of the simulation programs, and Appendix B includes the program codes.

II. OPERATING PRINCIPLES OF STEP FREQUENCY RADAR

A. STEP FREQUENCY WAVEFORM

The step frequency waveform can be described as an interpulse version of the common linear FM pulse compression waveform. A series of N coherent pulses are transmitted whose frequencies are monotonically increased from pulse to pulse by a fixed frequency increment ΔF as shown in Figure 2.1. Each pulse has a fixed pulse width τ , and the pulses are transmitted at a fixed pulse repetition frequency (PRF) [Ref. 5:pp. 160-161]. The frequency of the k th pulse is given by

$$f_k = f_o + (k - 1)\Delta F \quad (2.1)$$

where f_o is the nominal carrier frequency, and ΔF is the frequency step size.

The instantaneous bandwidth of this waveform is approximately equal to the inverse of the pulse width and is much less than the effective bandwidth. The waveform's effective bandwidth, denoted as B_{eff} , in contrast to the instantaneous bandwidth is determined by the product of the number of pulses N and the frequency step size ΔF :

$$B_{\text{eff}} = N\Delta F \quad (2.2)$$

The range resolution for any waveform is dependent on this effective bandwidth of the waveform. The range resolution of the step frequency waveform, in meters, is given as

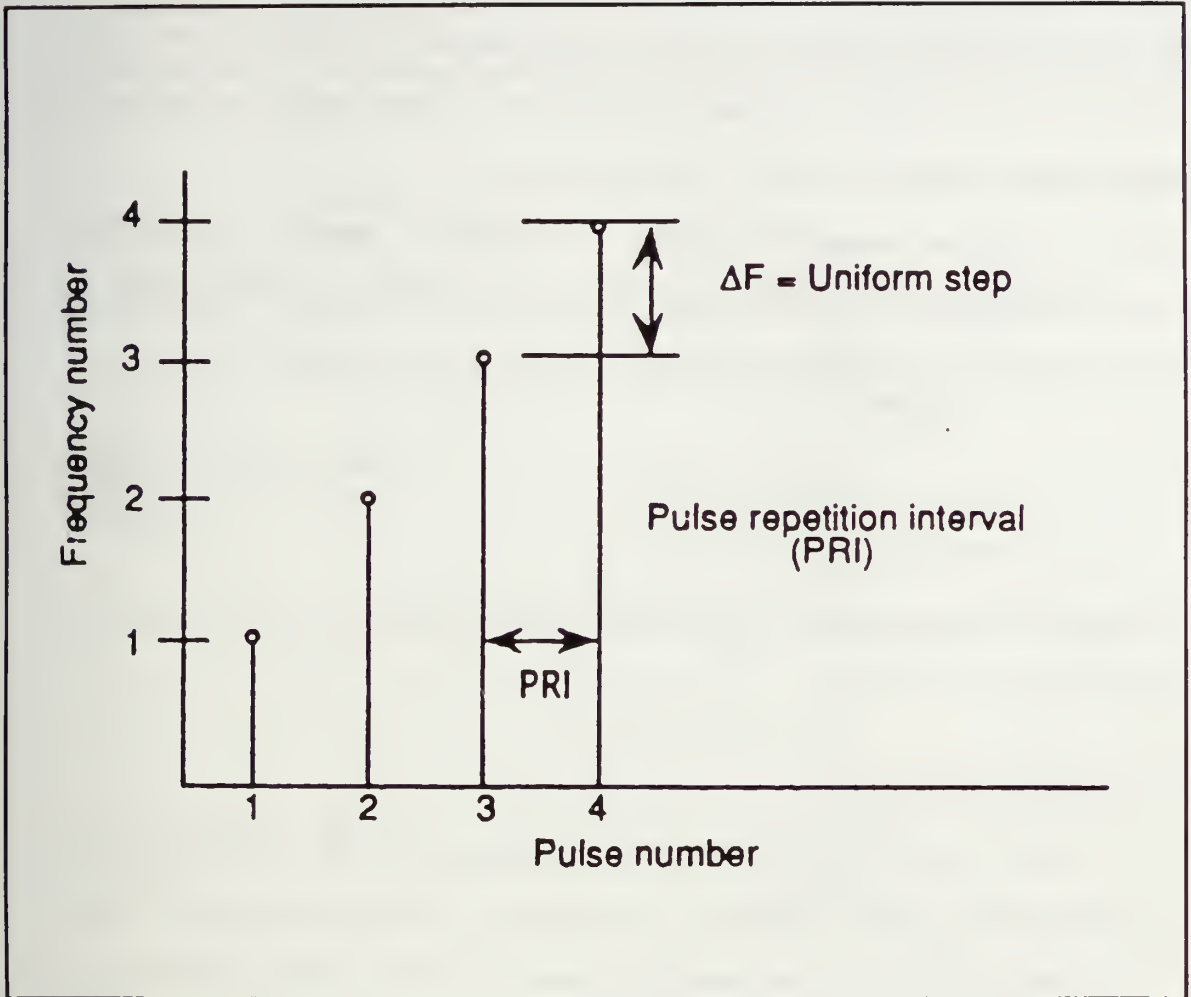


Figure 2.1 Step frequency waveform parameters. [Ref. 6.p. 235]

$$\Delta r = K \left(\frac{c}{2B} \right) = K \left(\frac{c}{2N\Delta F} \right) \quad (2.3)$$

where K is a constant determined by the weighting window and is greater than or equal to unity, and c is the speed of light (3×10^8 m/s). From equation (2.3), the range resolution can be made finer by either increasing the number of pulses and/or increasing the frequency step size. [Ref. 6:p. 234]

The coherent processing interval (CPI) is the total time duration in which echo returns are collected from a particular target for signal processing. The CPI is simply the product of the number of pulses N and the pulse repetition interval (PRI):

$$\text{CPI} = N(\text{PRI}) \quad (2.4)$$

The coherent processing interval is also referred to as the ramp repetition interval (RRI) or the burst time.

B. SYSTEM DESCRIPTION

The step frequency radar system consists of elements commonly found in a coherent pulse-doppler radar. A block diagram of a step frequency radar system is shown in Figure (2.2). A pulse is generated by first mixing the outputs of a fixed coherent oscillator at the IF frequency range (30-60 MHz) with a stepped frequency synthesizer whose frequency is stepped at a rate equal to the pulse repetition frequency (PRF). The sum frequency from the first mixer is then mixed with a stable, coherent RF frequency oscillator. The sum frequency of this second mixer is then pulse modulated and amplified prior to being transmitted.

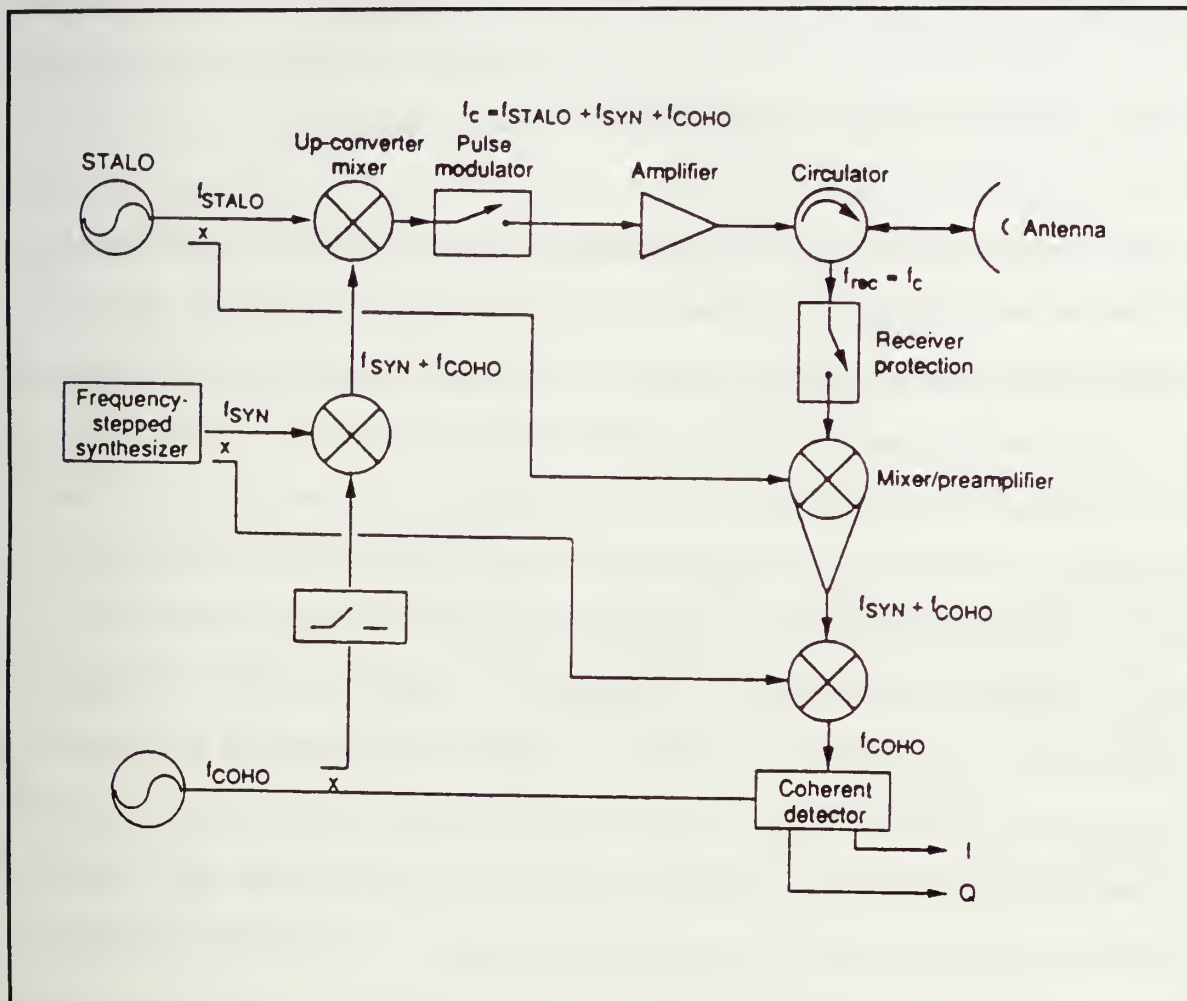


Figure 2.2 Block diagram of step frequency radar system used to obtain high range resolution (HRR) target profiles. [Ref. 6:p. 237]

The carrier frequency of each transmitted pulse is comprised of three elements: the fixed IF frequency of the coherent oscillator (COHO), the fixed RF frequency of the stable oscillator (STALO), and the variable frequency of the stepped frequency synthesizer. Thus, the carrier frequency of the k th pulse is given by the following equation:

$$f_{c_k} = f_{stalo} + f_{coho} + f_{syn_k} \quad (2.5)$$

The received pulse first passes through the duplexer and is then sent through an RF amplifier. After this stage, the return signal is mixed with the STALO, and the downconverted frequency is further mixed with the stepped frequency synthesizer. The stepped frequency synthesizer is synchronized so that the transmitter and receiver are on the same frequency step within the PRI. As a result multiple time around echoes will have frequencies which will vary by multiples of the frequency step size ΔF . The difference frequency between the downconverted STALO output and the second mixer (i.e. the stepped synthesizer) is the IF frequency. The signal is then passed through an IF amplifier which serves as a matched filter for the echo return. The bandwidth of the filter is approximately the inverse of the pulse width. Thus, multiple time around echoes whose IF frequencies fall outside the filter bandwidth will be rejected. The amplified signal is then split into two separate channels. The first channel is mixed with the coherent oscillator directly, and the second channel is mixed with the COHO signal after it has undergone a 90 degree phase shift. The difference frequencies in channels one and two comprise the in-phase (I) and quadrature (Q) components respectively. Each of the I and Q components are in the video frequency range. [Ref. 6:pp. 236-237]

Both the in-phase and quadrature signals are sent through an analog to digital converter (A/D) whose outputs are sampled at a rate equal to the inverse of one pulse

width. The I and Q samples for each range bin are stored in memory until all the pulses within the burst have been received for processing. Complex samples for each range bin are transformed by an inverse FFT to form the high resolution range profile (HRR profile) for that range bin. To reduce sidelobes in the range profile, the I and Q samples are usually windowed prior to computing the inverse FFT.

One of the key advantages of a step frequency radar compared to radars using other wideband waveforms is that the narrow instantaneous bandwidth eliminates the requirement for extremely high analog to digital conversion rates which can be a major limiting factor in the system design. The major limitation in the step frequency method is the time required to transmit and receive N pulses to achieve the desired fine range resolution.

C. WAVEFORM PROCESSING

As opposed to conventional radars, the pulses within one coherent processing interval have different carrier frequencies. The target return from a pulse at a specific frequency is the magnitude of the target reflectivity at that frequency. The collection of these samples from N pulses at N frequencies essentially constitutes a frequency spectrum.

The return signal consists of a video signal comprised of in phase and quadrature components as given by:

$$I(k) = A_k \cos \Phi_k \quad (2.6)$$

bandwidth

$$Q(k) = A_k \sin \Phi_k \quad (2.7)$$

and the complex samples are then formed as

$$S(k) = I(k) - jQ(k) = A_k \exp(-j\Phi_k) \quad (2.8)$$

where

$$\Phi_k = 2\pi f_k t_k \quad (2.9)$$

$$t_k = \frac{2R_k}{c} \quad (2.10)$$

and f_k refers to the k th frequency step of the frequency stepped synthesizer, and t_k denotes the round trip time due to a stationary scatterer at range R . Processing of received signals can be interpreted as converting frequency domain target reflectivity data via the inverse Fourier transform into the time domain to form the high range resolution (HRR) profile.

If the target's velocity is in the radar's line of sight, the target's range can be generalized to become

$$R_k = R_o + (k-1)vT \quad (2.11)$$

where R_o refers to the initial range at which the target is detected, v is the radial velocity of the target, and T equals the PRI. A positive radial velocity indicates an opening target,

and a negative radial velocity indicates a closing target. Moreover, a single point scatterer with a constant velocity is assumed in these equations.

The overall expression for the baseband return signal can be determined by substituting the instantaneous frequency from equation (2.1), the phase from equation (2.9), the round trip time from equation (2.10), and the target range from equation (2.11) into the expression for $s(k)$ in equation (2.8). The resulting expression is given by:

$$S(k) = A_k \exp(-j \frac{4\pi}{c} \underbrace{[f_o + (k-1)\Delta F]}_{f_k} \underbrace{[R_o + (k-1)vT]}_{\text{total range}}) \quad (2.12)$$

Expanding the expression inside the exponent in equation (2.12) results in a nonlinear phase term which causes range-doppler coupling for moving targets. The degree of range-doppler coupling profoundly impacts the range resolution of moving targets, as well as the integration gain of the signal processing [Ref. 7:pp. 4-5]. A complete description of these effects will be discussed in a later section. The set of N sampled baseband signals, $S(k)$, from a given range bin of width $c\tau/2$ are converted to a time domain range profile by the inverse FFT [Ref. 6:p. 238]:

$$s(n) = \frac{1}{N} \sum_{k=1}^N S(k) \exp\left(j \frac{2\pi kn}{N}\right), \quad 0 \leq n \leq N-1 \quad (2.13)$$

1. Phase Relationships of Return Signals of Successive Pulses

The phase of a target return from a given range for a specific pulse is obtained from equations (2.9) and (2.10) and is given by:

$$\Phi_k = \frac{4\pi f_k R_k}{c} \quad (2.14)$$

The step frequency method produces an induced phase shift between successive pulses because of the shift in the carrier frequency from pulse to pulse. The time rate of change of the phase is given by:

$$\frac{d(\Phi_k)}{dt} = \frac{4\pi}{c} \frac{d(f_k R_k)}{dt} = \frac{4\pi R_k}{c} \dot{f}_k + \frac{4\pi f_k}{c} \dot{R}_k \quad (2.15)$$

The corresponding frequency is given as:

$$f_t = \frac{1}{2\pi} \frac{d(\Phi_k)}{dt} = \frac{2R_k}{c} \dot{f}_k + \frac{2f_k}{c} \dot{R}_k \quad (2.16)$$

The rate at which the phase shifts from pulse to pulse depends on two components, as in equation (2.16). The first component is the rate of change of the instantaneous carrier frequency, f_k . The second component is the Doppler shift of the target caused by relative motion in the radial line of sight. If the relative motion between the target and the radar is negligible, equation (2.16) can be approximated as follows: [Ref. 6:p. 239]

$$f_t = f_{ips} \cong \frac{2R_k}{c} \frac{\Delta F}{T} \cong \frac{2R_k}{c} \Delta F \cdot f_{PRF} \quad (2.17)$$

The maximum unambiguous range is that for which the induced phase shift frequency equals the PRF. Therefore, the maximum unambiguous range of the high resolution range profile is given as:

$$R_u = \frac{c}{2\Delta F} \quad (2.18)$$

The unambiguous range is inversely proportional to the frequency step size. The above expression is similar to the unambiguous range for a conventional radar except that the frequency step size appears in the denominator instead of the PRF. If ΔF is 1 MHz, the unambiguous range will be 150 meters which is very small in comparison to conventional radars. As a consequence, any target with a range which is a multiple of the unambiguous range will be folded into the range profile resulting in range ambiguity. For example, targets with ranges of 100 meters, 250 meters, 400 meters, etc. will all appear in the same location in the HRR profile. Therefore, one cannot obtain absolute ranges to individual scatterers. Instead, the HRR profile gives relative range positions of scatterers contained within one pulse width. [Ref. 6.p. 243]

2. Range Bin Transformation

The original range resolution cell of the step frequency radar prior to taking the inverse FFT is determined by the pulse width and is given by:

$$\Delta r_{\text{orig}} = \frac{c\tau}{2} \quad (2.19)$$

where τ is the pulse width (if pulse compression has been used earlier, τ refers to the compressed pulse width). As a result of the signal processing, the unambiguous range

window of width R_u is split into N fine range resolution cells whose width (assuming no range weighting functions so that, K , the resolution loss factor due to windowing, is set to unity) is equal to

$$\Delta r = \frac{R_u}{N} = \frac{c}{2N\Delta F} \quad (2.20)$$

The fraction of the unambiguous range window R_u which is occupied by the original range bin Δr_{ong} is given as follows:

$$\frac{\Delta r_{\text{ong}}}{R_u} = \frac{\frac{c\tau}{2}}{\frac{c}{2\Delta F}} = \tau\Delta F \quad (2.21)$$

The original range bin is subdivided into finer range bins. The number of processed range bins corresponding to the original range bin is equal to:

$$\frac{\Delta r_{\text{ong}}}{\Delta r} = (\tau\Delta F) \cdot N \quad (2.22)$$

3. The Implications of the Product $\tau\Delta F$

The product of the pulse width and the frequency step size has major consequences on the nature of the HRR profile. In general, there are three possible outcomes.

When $\tau\Delta F$ is equal to one, the unambiguous range window, R_u , equals the original range bin size of $c\tau/2$. In effect, the old range bin is split into N segments with

each segment having a range resolution equal to Δr . This situation represents the minimum required sampling rate in the frequency domain for a given pulse width. It should be noted that the sampling rate in the frequency domain is equal to the frequency step size. The drawback to setting $\tau\Delta F$ to unity is that it becomes difficult to notice the wraparound of scatterer peaks caused by slight changes in target range. Moreover, aliasing may occur if there is interference from adjacent original range bins [Ref. 7:p. 7]. Finally, if the original range cell contains a moving target and clutter, the target will be masked by clutter. [Ref. 5:pp. 168-169]

When $\tau\Delta F$ is less than one, the original range bin comprises only a fraction of the unambiguous range window. This situation represents oversampling in the frequency domain and leads to a loss of resolution in the range profile. However, the unused portion of the range profile represents a clutter free zone which can be used to detect moving targets.

When $\tau\Delta F$ is greater than one, the unambiguous range window is smaller than the original range bin. This situation represents undersampling in the frequency domain. As a result, those regions of the original range bin not contained within the unambiguous range window will fold over resulting in aliasing of the HRR profile. This situation must be avoided for mapping range profiles. [Ref. 8:pp. 602-603]

One basic requirement in choosing the frequency step size is that the unambiguous range window, R_u , must encompass the maximum target extent E to avoid target wraparound, as shown below, or expressed alternatively in equation (2.24):

$$R_u = \frac{c}{2\Delta F} \geq E \quad (2.23)$$

$$\Delta F \leq \frac{c}{2E} \quad (2.24)$$

An additional requirement for good detectability is that the pulse width must encompass the maximum target extent. If the pulse width does not encompass the target extent, different scatterers within the target will not be located within the same original range bin resulting in a loss of SNR [Ref. 6:p. 245]. To encompass the target extent, the pulse width must be greater than or equal to the round trip time from the nearest point of the target to the farthest point on the target, given by

$$\tau \geq \frac{2E}{c} \quad (2.25)$$

D. EFFECTS OF RADIAL VELOCITY ON THE RANGE PROFILE

Radial velocity between the radar and the target results in additional pulse to pulse phase shift caused by the Doppler effect. The second component in equation (2.16) represents the Doppler frequency shift and can be rewritten as

$$f_d = \frac{2f_k}{c} \dot{R}_k = \frac{2v}{\lambda_k} \quad (2.26)$$

where λ_k is the wavelength of the k th pulse, and v is the relative radial velocity between the radar and the target. The additional phase shift due to the radial velocity results in a mismatch in the inverse FFT which acts as matched filter for the stepped frequency waveform only if the radial velocity is equal to zero [Ref. 7:p. 44]. The consequences of the mismatch in the inverse FFT have three major effects on the range profile.

The first effect is an attenuation of the peak signal level of the scatterer. Since the mean noise level remains the same, this results in a reduction in the signal to noise ratio (SNR). The second effect is the dispersion or spreading of the peak signal into adjacent range bins. The amount of dispersion is determined by a dimensionless parameter, P , which represents the number of range bins the signal spreads in one coherent processing interval:

$$P = \frac{vN(\text{PRI})}{\Delta r} \quad (2.27)$$

The effects on the signal peak for different values of P are shown in Figure 2.3. In general, the dispersion factor, P , should be kept below three for reasonable performance [Ref. 7:p. 5]. In effect, the dispersion of the signal results in a loss of range resolution because the peak has broadened from one range bin of width Δr to several range bins whose width is equal to $P\Delta r$. One should note that the dispersion can be effectively reduced by increasing the PRF of the radar, without having to adjust the number of pulses N or the frequency increment ΔF . [Ref. 7:p. 46]

The third effect of radial velocity is a shifting of signal peaks in the HRR profile. This effect is similar to the range-doppler coupling effects in conventional linear FM pulse compression waveforms. In addition to the dispersion or broadening of the peak, the location of the peak is shifted by L range bins where L represents the bin shift factor and is given by: [Ref. 7:p. 45]

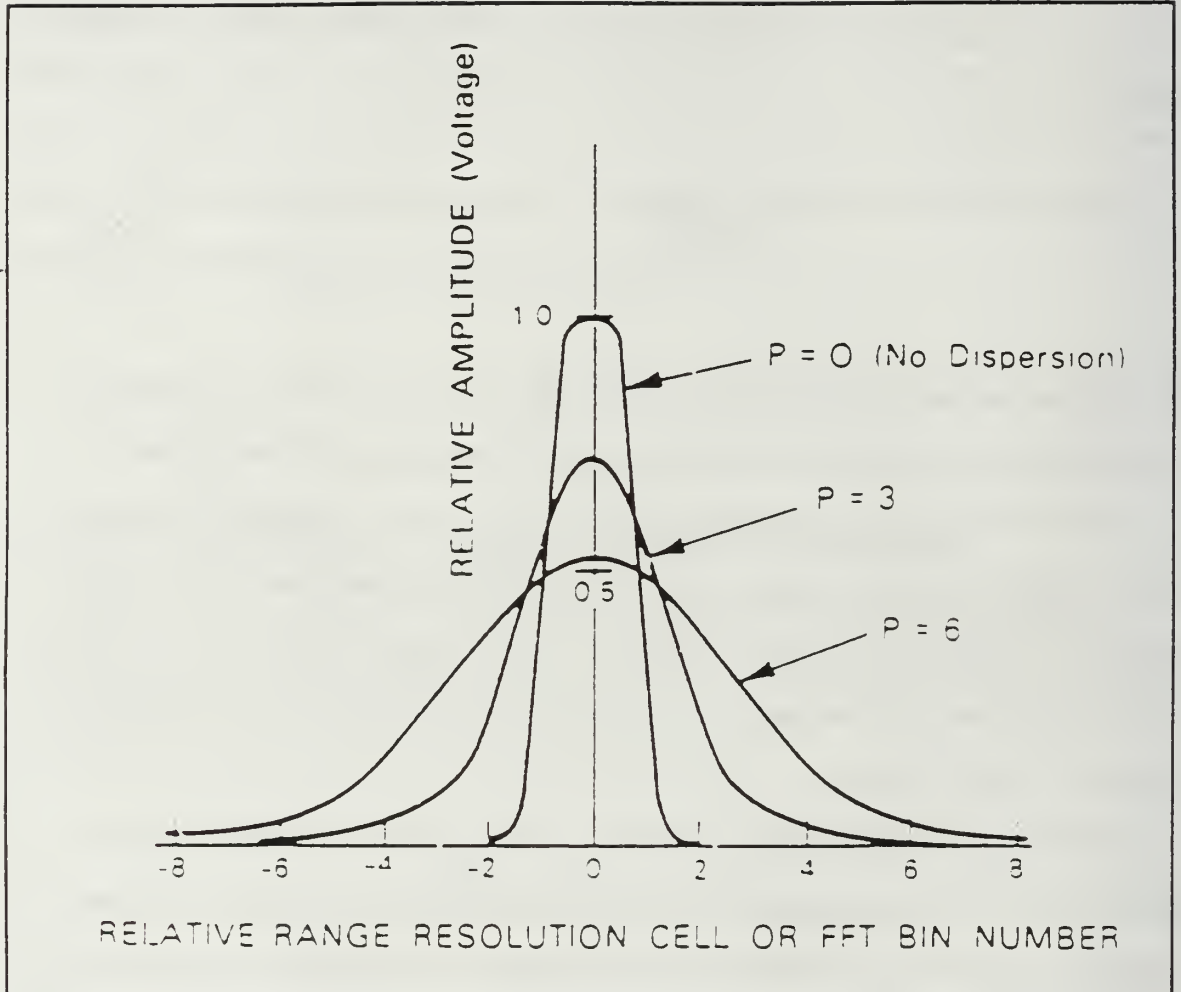


Figure 2.3 The effect on the signal peak for various values of the dispersion factor P [Ref. 7 p 47]

$$L = \left\lceil \frac{\hat{f}_c}{B_{\text{eff}}} \right\rceil P = f_d N(\text{PRI}) \quad (2.28)$$

where

$$\hat{f}_c = f_o + \frac{1}{2} B_{\text{eff}} \quad (2.29)$$

The number of shifted range bins, L , is directly proportional to the dispersion factor P . The factor \hat{f}_c is the median value of the carrier frequency within one coherent processing interval [Ref. 7:p. 45]. If the sum of the bin shift factor and the original bin location of the signal peak exceeds the N pulses used in the inverse FFT, the signal peak will wraparound from the beginning of the HRR resulting in an aliased profile. It will be difficult to tell from the HRR whether the target peak is in its actual position, or has been wrapped around several times due to radial motion. The bin shift factor represents the number of shifted range bins from the original peak location to the beginning of the broadened shifted peak, not the center of the shifted peak.

One way to reduce the effects of radial velocity is to apply velocity compensation to the frequency domain data prior to taking the inverse FFT. Assuming that all scatterers within a single target have the same known radial velocity, one can cancel the mismatch by multiplying the returns from the approximate range location of the target by a correction factor [Ref. 6:p. 253]. The expression for the correction factor is given as:

$$V_c(k) = \exp\left(\frac{j4\pi}{c} v(f_o + (k-1)\Delta F)(k-1)T\right) \quad (2.30)$$

where $V_c(k)$ is the compensation applied to the signal return of the k th pulse by multiplying it with $S(k)$. The key limitation in applying a compensation factor is that the target velocity must be known in advance by another method, or be given by another radar. Errors in the compensated speed are most significant if the sign of the velocity is estimated incorrectly. For example, if the true target velocity is +300 m/sec (opening target) and the compensated velocity is -300 m/sec (closing target), the resulting dispersion will prevent the target peak from being observed in the range profile.

In summary, the step frequency waveform consists of transmitting and receiving a series of N coherent pulses whose frequencies change by a fixed amount ΔF . The wide effective bandwidth equals the product of the number of pulses, N , and the frequency step size, ΔF . It is this effective bandwidth, achieved over several pulses, which results in the fine processed range resolution. The step frequency radar system is similar to conventional narrowband systems with the addition of a stepped frequency synthesizer.

Frequency domain reflectivity data are coherently processed by the inverse FFT to produce the high resolution range profile for each original range bin. The fraction of the HRR profile occupied by the original range bin is given by the product $\tau\Delta F$. This product must be less than or equal to unity to prevent aliasing.

Radial velocity between the radar and the target results in dispersion of the target range profile, target range shift caused by range-doppler coupling, and a reduction in SNR. Proper velocity compensation corrects these deficiencies but requires advance knowledge of the correct target velocity. If velocity compensation is not possible, increasing the PRF will alleviate the effects of target motion on the HRR profile.

III. DESIGN METHODOLOGY FOR STEP FREQUENCY RADAR

The design of a step frequency radar system requires a thorough understanding of the effects of the primary design parameters on the overall system performance. These primary design parameters consist of the following:

1. N , the number of pulses within a coherent processing interval
2. ΔF , the frequency step size
3. f_{PRF} , the pulse repetition frequency
4. τ , the pulse width (compressed pulse width if pulse compression is used)

Once the effects of these individual parameters are known, then it is possible to determine optimal combinations of parameters to achieve certain specified design goals. The design process is shaped by the operational requirements determined by the user, as well as the environment in which the radar will function.

A. EFFECTS OF INDIVIDUAL PARAMETERS

In this section, all other parameters are assumed to be held constant while the parameter of interest is being increased.

1. Increase N , the number of pulses

An increase in the number of frequency steps N within a coherent processing interval will increase the effective waveform bandwidth:

$$B_{eff} = N\Delta F \quad (3.1)$$

The increased bandwidth will result in a finer processed range resolution, Δr , since the range resolution is inversely proportional to the waveform bandwidth:

$$\Delta r = \frac{Kc}{2B_{\text{eff}}} \quad (3.2)$$

An increase in N will also lead to a longer coherent processing interval (CPI), which is the product of the number of pulses in a burst and the PRI which requires a longer dwell time. The longer processing time will also lead to a finer frequency resolution in the FFT since

$$\Delta f_{\text{res}} = \frac{Kf_{\text{PRF}}}{N} \quad (3.3)$$

For moving targets, an increase in the number of pulses will lead to a large increase in the dispersion factor P ($P \propto N^2$) and an increased bin shift factor L , given by

$$P = \frac{vN}{f_{\text{PRF}} \Delta r} = \frac{vN}{f_{\text{PRF}} \frac{Kc}{2N\Delta F}} = \frac{2vN^2 \Delta F}{f_{\text{PRF}} Kc} \quad (3.4)$$

$$L = \frac{\hat{f}_c}{B_{\text{eff}}} \frac{vN}{f_{\text{PRF}} \Delta r} = \frac{\hat{f}_c}{N\Delta F} \frac{vN}{f_{\text{PRF}} \frac{Kc}{2N\Delta F}} = \frac{2\hat{f}_c vN}{f_{\text{PRF}} Kc} \quad (3.5)$$

2. Increase ΔF , the frequency step size

An increase in the frequency increment between pulses will increase the waveform bandwidth as in equation (3.1) and results in a finer processed range resolution as in equation (3.2). In addition, increasing the frequency step size will decrease the unambiguous range window since

$$R_u = \frac{c}{2\Delta F} \quad (3.6)$$

For moving targets, increasing the frequency step size will increase the dispersion of the target peak as in equation (3.4). However, ΔF does not influence the bin shift factor L as indicated in equation (3.5). Increasing the frequency spacing between pulses without regard for the pulse width can lead to aliasing in the range profile if the product of $\tau\Delta F$ exceeds unity. Aliasing will also occur if

$$\Delta F > \frac{c}{2E} \quad (3.7)$$

3. Increase the PRF

An increase in the PRF will lead to both improved and earlier detection of targets. The radar range equation written in terms of the peak power, P_t , is given by

$$R_{\max}^4 = \frac{P_t G^2 \lambda^2 n \sigma}{\left(\frac{S}{N}\right)_{\min} (4\pi)^3 k T_o B_f FL} \quad (3.8)$$

where:

- P_t = the peak power of the transmitter in watts
- G = the antenna gain of the transmit/receive antenna (assumed to be equal)
- λ = the radar wavelength in meters
- n = the number of pulses coherently integrated within one scan
- σ = the radar cross section of the target in square meters
- R = the detection range of the target in meters
- k = Boltzmann's constant (1.38×10^{-23})
- T_o = the noise temperature in degrees Kelvin
- B_f = the radar's instantaneous bandwidth in Hertz
- F = the receiver noise figure
- L = a loss factor incorporating all other system losses.

Equation (3.8) can be rewritten as:

$$\left(\frac{S}{N} \right)_{\min} = \frac{P_{\text{avg}} G^2 \lambda^2 n \sigma}{R_{\max}^4 (4\pi)^3 k T_o F L f_{\text{PRF}}} \quad (3.9)$$

where

$$P_{\text{avg}} = P_t \frac{\tau}{T} \quad (3.10)$$

As indicated in equation (3.9), the minimum SNR needed to detect a target at a given range R , is inversely proportional to the PRF resulting in improved detection as the PRF is increased.

Increasing the PRF will also reduce the range-doppler coupling for moving targets since both the dispersion and bin shift factors are inversely proportional to the PRF as shown in equations (3.4) and (3.5). For noise limited situations, the reduction in range-doppler coupling eases the velocity compensation requirements and reduces the chances of aliasing for uncompensated range profiles. Although increasing the PRF will reduce the chances of aliasing in clutter limited situations, it may, however, prevent the migration of the target peaks into the clutter free region which is required for target detection in the presence of strong clutter. The PRF has no effect on the range profiles of stationary targets in either a noise limited or clutter limited situation. Furthermore, the PRF has no effect on the processed range resolution Δr or the unambiguous range window R_u as in equations (3.2) and (3.6) respectively. The inverse FFT operation yields the HRR profile containing N range bins with a resolution of Δr , which does not depend on the PRF.

4. Increase τ , the pulse width

An increase in the pulse width will increase the energy or average power directed at the target which in turn will lead to both earlier detection for a fixed SNR, or a reduced minimum SNR to detect a target at a given range, as follows

$$R^4_{\max} = \frac{(P_t \tau) G^2 \lambda^2 n \sigma}{\left(\frac{S}{N}\right)_{\min} (4\pi)^3 k T_o FL} = \frac{E G^2 \lambda^2 n \sigma}{\left(\frac{S}{N}\right)_{\min} (4\pi)^3 k T_o FL} \quad (3.11)$$

$$\tau \geq \frac{2E}{c} \quad (3.12)$$

However, for fine range profiling (i.e. mapping of stationary targets), this condition need not be met.

B. SUMMARY OF EQUATIONS RELATING DESIGN PARAMETERS

Equations relating the important design parameters are summarized below in Table 3.1.

TABLE 3.1 EQUATIONS RELATING IMPORTANT DESIGN PARAMETERS

Design Parameter	Equation	Design Parameter	Equation
Processed Range Resolution	$\Delta r = \frac{Kc}{2N\Delta F}$	Dispersion Factor	$P = \frac{vN}{f_{PRF}\Delta r}$
Effective Waveform Bandwidth	$B_{eff} = N\Delta F$	Range Bin Shift Factor	$L = \frac{\hat{f}_c vN}{Bf_{PRF}\Delta r}$
Unambiguous Range Window	$R_u = \frac{c}{2\Delta F}$	Clutter Free Fraction of Range Profile	$\frac{\Delta r}{R_u} = \tau\Delta F$

unambiguous
detection range

$$R_{unamb} = \frac{c}{2\Delta F}$$

C. DESIGN METHODS FOR THE STEP FREQUENCY WAVEFORM

The following section contains various design methods to achieve high range resolution in either noise limited or clutter limited situations using the step frequency waveform. For each method, the principal requirements, the adjustable parameters, and key assumptions will be stated prior to the detailed description of the various design steps. Each of these methods assumes a low PRF mode of operation, which results in unambiguous initial target ranges out to the maximum detection range.

1. Design Method No. 1: clutter environment

This design method is based on the assumption that clutter is the limiting factor in the detection of targets. The effects of thermal noise on the range profile are minimal compared to clutter. This situation would be expected if the main beam is pointed downward. The principal requirements are as follows:

1. Processed range resolution, Δr (meters)
2. Maximum target detection range (unambiguous), R_{unamb} (meters)
3. Maximum target extent, E (meters)
4. Minimum and maximum target radial velocities, v_{min}, v_{max} (m/s)

The adjustable design parameters are as follows:

1. Frequency step size, ΔF (Hz)
2. Pulse width, τ (seconds)
3. Number of pulses within coherent processing interval, N
4. Pulse repetition frequency, PRF (Hz)
5. Clutter Free portion of HRR (expressed as fraction of entire profile)
6. Time on Target, T_{tot} (seconds)

The design process consists of the following steps in the order shown below:

1. From the required processed range resolution, calculate the waveform bandwidth:

$$B_{\text{eff}} = N\Delta F = \frac{Kc}{2\Delta r} \quad (3.13)$$

2. Determine the pulse width necessary for the pulse to encompass the target for good detectability. However, a larger pulse width will also increase the amount of clutter in the range cell:

$$\tau \geq \frac{2E}{c} \quad (3.14)$$

3. Determine the percentage of clutter free space in the range profile. The fraction of the range profile containing clutter is specified by the following equation:

$$\frac{c\tau}{2R_u} = (\tau\Delta F) \quad (3.15)$$

Choosing a low value for the product $\tau\Delta F$ (i.e. 0.1) will increase the fraction of clutter free space which will result in improved detection of moving targets.

However, it will worsen the processed range resolution. Conversely, choosing values of $\tau\Delta F$ close to unity will eliminate the clutter free space where targets may be detected. Also, fast moving targets are likely to wrap around for high values of $\tau\Delta F$, which will degrade their detectability. The product $\tau\Delta F$ must not exceed unity in order to prevent aliasing.

4. The frequency step size can be specified as the following:

$$\Delta F = \frac{(\tau \Delta F)_{reqd}}{\tau} \quad (3.16)$$

The value of ΔF determined by equation (3.16) must also satisfy the following requirement shown below to prevent aliasing:

$$\Delta F \leq \frac{c}{2E} \quad (3.17)$$

If the value of the step size exceeds the constraint of equation (3.17), the appropriate course of action is to reduce the frequency step size so that equation (3.17) is satisfied and then to increase the pulse width as needed to maintain the desired amount of clutter free space (i.e. keep $\tau \Delta F$ constant).

5. Determine the number of frequency steps N based on the required bandwidth and the computed frequency step size:

$$N = \frac{B_{eff}}{\Delta F} \quad (3.18)$$

6. Select the PRF based on the following considerations:

A. The upper bound will be determined by the PRF needed to move the slowest target from the beginning of the clutter region to just outside the clutter region.

i. The number of bins in clutter region equals $(\tau \Delta F)N$
(one pulse width)

- ii. The required amount of bins to be shifted equals $(\tau\Delta F)N$
(to move the target outside the clutter region)
- iii. The bin shift factor L is given as:

$$L = \frac{\hat{f}_c v_{\min} N}{B_{\text{eff}} \Delta r (f_{\text{PRF}})_{\text{upper}}} \quad (3.19)$$

- iv. Set the bin shift factor equal to the number of bins to be shifted:

$$\frac{\hat{f}_c v_{\min} N}{B_{\text{eff}} \Delta r (f_{\text{PRF}})_{\text{upper}}} = (\tau\Delta F)N \quad (3.20)$$

- v. After simplification, the upper bound on the PRF is:

$$(f_{\text{PRF}})_{\text{max}} = \frac{\hat{f}_c v_{\min}}{B_{\text{eff}} \Delta r \Delta F \tau} \quad (3.21)$$

B. The lower bound on the PRF will be determined as that PRF which will cause the target at the end of the clutter region with the maximum expected velocity to the upper edge of the unambiguous range window without wrap around:

- i. The number of range bins from the end of the clutter region to the upper edge of the range profile equals $N(1 - \tau\Delta F)$.
- ii. Set this above quantity equal to the expression for the bin shift factor L , and solve for the resulting PRF:

$$(f_{\text{PRF}})_{\min} = \frac{\hat{f}_c v_{\max}}{B_{\text{eff}} \Delta r (1 - \tau \Delta F)} \quad (3.22)$$

If $(\tau \Delta F) = 0.5$, and target velocity is constant, the upper and lower bounds are equal

The underlying rationale in determining the upper and lower bounds of the PRF is that an increase in the PRF will reduce the range-doppler coupling resulting in a reduction in both the number of bins that the target peak shifts and the dispersion of the peak. As a result, the PRF must not be so high to the point where the bin shift is insufficient to cause the moving target to migrate to the clutter free zone. Conversely, too low a PRF will increase the range-doppler coupling which may cause the target peak to wrap around.

7. The time on target is determined by the PRF and the number of frequency steps:

$$T_{\text{tot}} = \frac{N}{f_{\text{PRF}}} \quad (3.23)$$

The PRF that is chosen must lie in the range specified by equations (3.21) and (3.22). However, the value chosen must result in an unambiguous range greater than or equal to the maximum target detection range. If no PRF value within the range satisfies the unambiguous maximum target range requirement, then the system must be redesigned for a different range of target velocities or for a different maximum target detection range.

2. Design Method No. 2: noise environment

This design method is based on the assumption that the effects of clutter are negligible. This assumption is valid in situations where the main beam is elevated upward. The design steps do not assume that velocity compensation has been applied to the profile.

Velocity compensation can be included at the discretion of the radar designer if the performance requirements cannot be met otherwise. The principal requirements are as follows:

1. Processed range resolution, Δr (meters)
2. Maximum target detection range (unambiguous), R_{unamb} (meters)
3. Maximum target extent, E (meters)
4. Target radial velocity, v (m/s)
5. Allowable range-doppler coupling expressed in terms of maximum bin shift and dispersion.

The adjustable design parameters are as follows:

1. Frequency step size, ΔF (Hz)
2. Pulse width, τ (sec)
3. Number of pulses within coherent processing interval, N
4. Pulse repetition frequency, PRF (Hz)
5. Time on target, T_{tot} (sec)

The design process consists of the following steps in the order listed below:

1. From the required processed range resolution, calculate the waveform bandwidth:

$$B_{\text{eff}} = N\Delta F = \frac{Kc}{2\Delta r} \quad (3.24)$$

2. For good target detectability, determine the pulse width necessary to encompass the target:

$$\tau \geq \frac{2E}{c} \quad (3.25)$$

This requirement need not be met if target mapping is the primary concern.

3. Determine the fraction of the unambiguous range window which is occupied by the returns from an original range bin of width $c\tau/2$. This fraction is given by equation (3.15) as being equal to the product $\tau\Delta F$. To avoid aliasing of the profile, $\tau\Delta F$ cannot exceed unity. In the absence of strong clutter, this product should be set at or near unity to provide fine processed range resolution.
4. The frequency step size, ΔF , can be determined by simply dividing the value of $\tau\Delta F$ by the pulse width:

$$\Delta F = \frac{(\tau\Delta F)}{\tau} \quad (3.26)$$

Provided that $\tau\Delta F$ is less than or equal to unity, the frequency step size determined by equation (3.26) automatically satisfies the criterion that

$$\Delta F \leq \frac{c}{2E} \quad (3.27)$$

which is the required sampling rate in the frequency domain.

5. Determine the number of frequency steps N based on the required bandwidth and the computed frequency step size:

$$N = \frac{B_{\text{eff}}}{\Delta F} \quad (3.28)$$

6. Choose the PRF as follows:

- A. For stationary targets, select the PRF based on the following considerations:

- i. Maximum unambiguous target detection range

$$R_{\text{unamb}} = \frac{c}{2f_{\text{PRF}}} \quad (3.29)$$

- ii. Transmitter average power

$$P_{\text{avg}} = P_t \tau(f_{\text{PRF}}) \quad (3.30)$$

- B. For moving targets:

- i. Select the PRF based on the maximum expected target radial velocity and the maximum tolerable bin shift, L_{max} :

$$f_{\text{PRF}} = \frac{\hat{f}_c v N}{B_{\text{eff}} \Delta r(L_{\text{max}})} \quad (3.31)$$

2. Alternatively, select the PRF based on the maximum expected target velocity and the maximum tolerable dispersion factor, P_{\max} :

$$f_{\text{PRF}} = \frac{vN}{\Delta r(P_{\max})} \quad (3.32)$$

The PRF chosen by either of these methods will be consistent since the maximum bin shift is proportional to the maximum dispersion factor:

$$L_{\max} = \left(\frac{\hat{f}_c}{B_{\text{eff}}} \right) P_{\max} \quad (3.33)$$

7. Determine the time on target based on the number of pulses and the PRF:

$$T_{\text{tot}} = \frac{N}{f_{\text{PRF}}} \quad (3.34)$$

Upon completion of these steps, one must check to ensure that the chosen PRF will not yield an unambiguous range in conventional radar terms (equation 3.29) that is less than the maximum detection range. If this is the case, then the PRF must be recomputed in step five with a different value of maximum target radial velocity or a less stringent maximum bin shift factor or a less stringent dispersion factor.

3. Design Method No. 3: noise environment, fixed time on target

This design method is based on the assumptions that the effects of clutter are negligible and the time on target is fixed by other design considerations such as the antenna beam width and antenna scan rate. Moreover, it is assumed that velocity compensation has not been applied to the range profile. The principal requirements are as follows:

1. Processed range resolution, Δr (meters)
2. Maximum target detection range (unambiguous), R_{unamb} (meters)
3. Maximum target extent, E (meters)
4. Time on target, T_{tot} (sec)

The adjustable design parameters are as follows:

1. Frequency step size, ΔF (Hz)
2. Pulse width, τ (sec)
3. Number of pulses within coherent processing interval, N
4. Pulse Repetition Frequency, PRF (Hz)

The design process consists of the following steps in the order listed below:

1. From the required maximum unambiguous target, calculate the PRF:

$$f_{\text{PRF}} = \frac{c}{2R_{\text{unamb}}} \quad (3.35)$$

2. Calculate the number of pulses N , based on the time on target, and the PRF:

$$N = T_{\text{tot}} (f_{\text{PRF}}) \quad (3.36)$$

3. For good detectability, determine the pulse width necessary to encompass the target:

$$\tau \geq \frac{2E}{c} \quad (3.37)$$

As in the previous design method, the fraction of the unambiguous range window occupied by the original range cell should be at or near unity, in the absence of strong clutter. However, the product $\tau\Delta F$ should not exceed unity to avoid aliasing.

4. Choose the frequency step size ΔF to obtain the required range resolution based on the number of pulses N determined in step one:

$$\Delta F = \frac{Kc}{2N\Delta r} \quad (3.38)$$

The major difference in this design method compared to the previous method is that the PRF is determined primarily by the time on target constraints which are determined by the antenna beam width and scan rate. As a result, the target radial velocity and maximum allowable bin shift no longer play a role in determining the PRF. Moreover, the number of pulses within the burst are determined by unambiguous range and time on target constraints. The frequency step size is then chosen based on the required range resolution and the precomputed number of frequency steps.

To summarize, the primary design parameters of a step frequency radar are the number of pulses, N , the frequency step size, ΔF , the PRF, and the pulse width, τ . Optimal combinations of these parameters are determined to achieve certain specified design goals. Design methods are developed for a low PRF mode of operation in clutter limited and noise limited environments.

IV. SIMULATION OF HRR PROFILES

A simulation program was developed using MATLAB to graphically show the effects of various step frequency waveform parameters on a synthetic range profile. The simulation output is the HRR profile corresponding to a given original range bin of width $c\tau/2$. There are three versions of simulation; one for noise limited situations, one for clutter limited situations, and one for clutter limited situations which includes clutter cancellation and velocity compensation. In the first two versions, a maximum of three moving targets within the original range cell can be specified. The third version simulates a single moving target. Moreover, all major waveform parameters such as the number of pulses N , the frequency increment ΔF , the PRF, and the carrier frequency can be specified. In addition, the signal to noise ratio (SNR) and the signal to clutter ratio (SCR) at the output of the IF filter can be specified for each target based on a reference value for a 1 m^2 target.

The noise source is modeled as white gaussian noise with a variance of 0.0002. The clutter sources are modeled as a series of ten closely spaced sinusoidal scatterers with fixed ranges within the original range cell. The magnitude of each clutter source is identical and is based on the signal to clutter ratio for a 1 m^2 target. A complete description of all three versions of simulation is given in Appendix A. The program codes are listed in Appendix B.

A. HRR PROFILES IN NOISE LIMITED SITUATIONS

In this section, the HRR profiles will be embedded in white gaussian noise with variance of 0.0002. The reference waveform parameters are listed in Table 4.1. The reference HRR profile is shown in Figure 4.1.

TABLE 4.1 REFERENCE PARAMETERS FOR HRR SIMULATION WITH NOISE

Parameter	Reference Value
Number of Pulses (N)	500
Frequency Step Size (ΔF)	10 MHz
Pulse Repetition Frequency (PRF)	50 kHz
Pulse Width (τ)	0.1 μ sec
Nominal Carrier Frequency (f_c)	1 GHz
Processed Range Resolution (Δr) (unweighted)	0.03 m
Unambiguous Range Window (R_u)	15 m = $\frac{12}{2}$ (design make the same)
Fraction of R_u occupied by original range bin ($\tau \Delta F$)	1
Range Weighting Function	Hamming (K=1.33)
Processed Range Resolution (Δr) (with range weighting function)	0.03 m
Initial Target Ranges	1204 m (T1), 1210 m (T2), 1212 m (T3)
Target Cross Sections	100 m ² (T1), 10 m ² (T2), 1 m ² (T3)
Target SNR	20 dB (T1), 10 dB (T2), 0 dB (T3)
Target Velocities	0 m/s (T1), 0 m/s (T2) 0 m/s (T3)

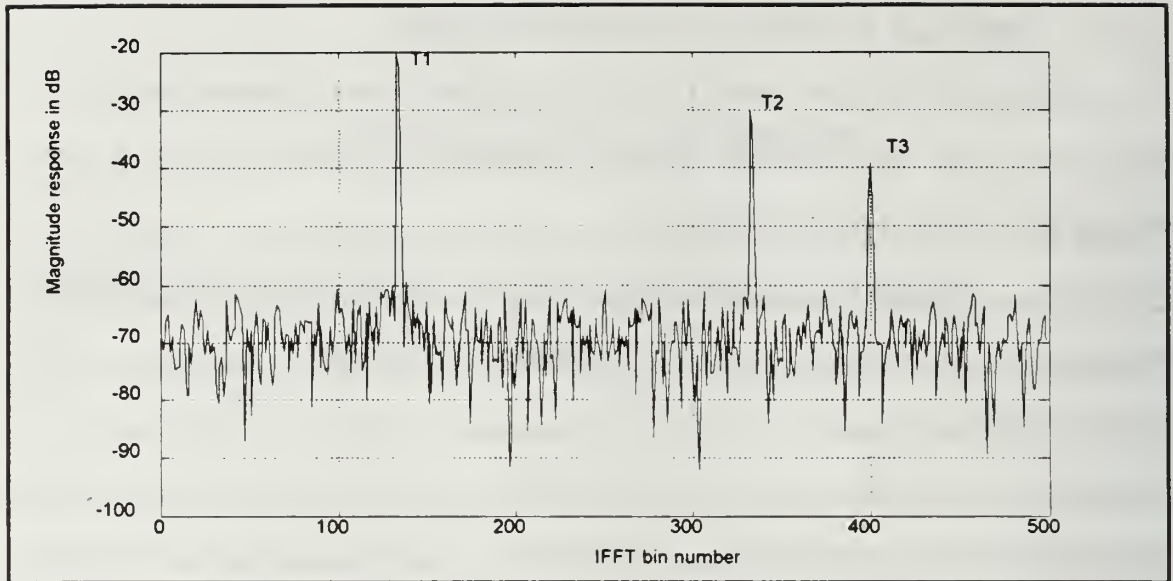


Figure 4.1 Reference HRR Profile with 3 stationary targets in white noise

Figure 4.1 clearly reveals the peaks corresponding to the three targets located at 1204 m, 1210 m, and 1212 m. The inverse FFT (IFFT) bin number of each target peak is directly related to the target range. To determine the IFFT bin number for a specific target range, the following steps are carried out. First, the modulo range, R_{mod} , is determined by dividing the target range, R_t , by the unambiguous range, R_u , as follows

$$R_{\text{mod}} = R_t \bmod R_u \quad \text{mod } \frac{1204}{15} \quad (4.1)$$

// remainder

The IFFT bin number corresponding to the modulo range is then given by

$$\frac{\text{bin}}{N} = \frac{R_{\text{mod}}}{R_u} \quad \text{IFFT}_{\text{bin}} = R_{\text{mod}} \left(\frac{N}{R_u} \right) \quad (4.2)$$

In this case, R_u equals 15 meters. The HRR profile in Figure 4.1 represents range from 1200 to 1215 meters.

The product $\tau\Delta F$ is set to unity in the reference profile which results in the original range bin of width $c\tau/2$ occupying the entire unambiguous range window R_u . This gives a processed range resolution of 0.03 meters unwindowed. However, the reference profile has been multiplied by a Hamming window to reduce the sidelobes of each target peak which results in a slight loss of range resolution from 0.03 m to 0.04 m. In the following subsections, the pulse width, τ , and the SNR will be held constant, and unless specified otherwise, all HRR profiles are multiplied by the Hamming window. The remaining parameters will be varied one at a time from their reference value, and the resulting effects on the range profile will be displayed.

1. Effect of Varying the Number of Pulses

Figure 4.2a shows the effect of increasing the number of pulses to 1000.

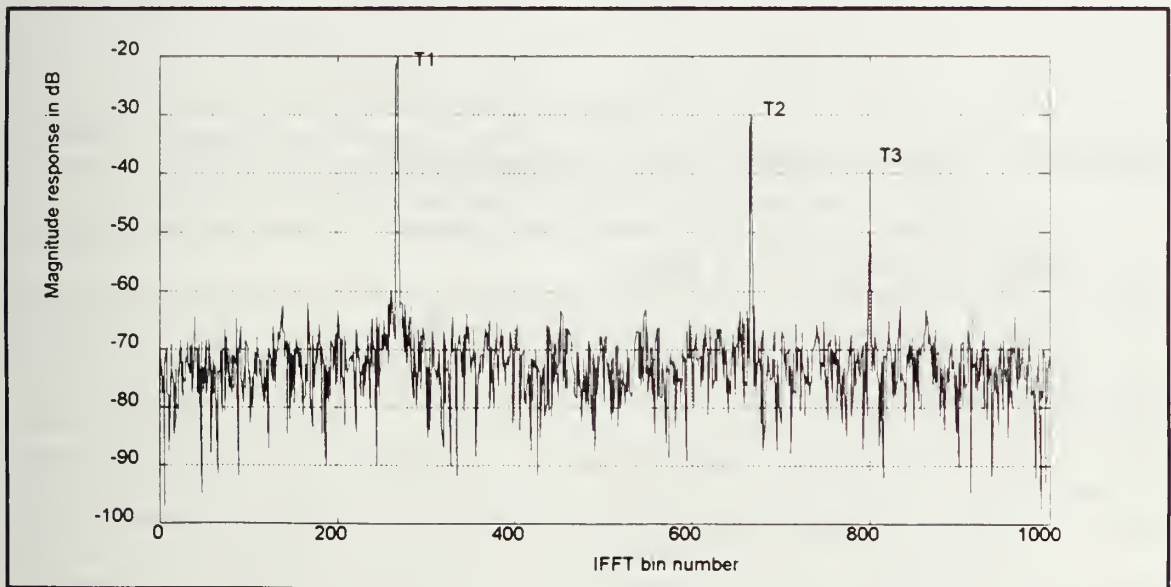


Figure 4.2a HRR Profile of three stationary targets in white noise. $N = 1000$.

The major change in increasing the number of pulses is the increased range resolution which is now 0.015 m (unweighted.) Moreover, there is an increase in the SNR due to the increase in processing gain due to coherently integrating 1000 instead of 500 pulses. If the number of pulses is reduced from the original number, the range resolution becomes

coarser, and the SNR decreases due to a reduction in processing gain. These results are shown in Figure 4.2b. In this figure, the number of pulses has been reduced to 250 which results in a range resolution of 0.06 m. The reduction in the number of pulses reduces the SNR gain to such an extent that the third scatterer is not detectable from noise.

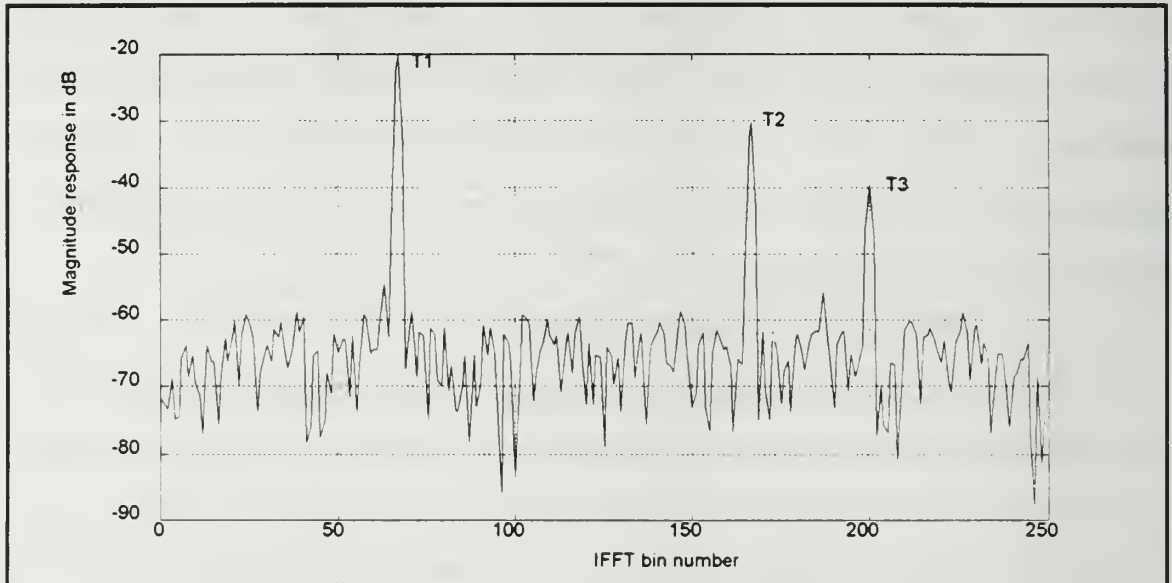


Figure 4.2b HRR Profile of three stationary targets in white noise. $N = 250$.
Note the third peak (bin 200) is not distinguishable from the noise.

2. Effect of a Shift in Target Range

One of the key features apparent from the HRR profile is that it is highly ambiguous in absolute range. Only relative scatterer position within the original pulse width is indicated in the profile. Targets located at multiples of the unambiguous range would all lie in the same relative position in the HRR profile. In addition, a slight shift in range position of the targets relative to the radar will cause the peaks to shift, and possibly wraparound, resulting in range ambiguities. For example, Figure 4.3 shows the range profile when the three targets each have shifted outward by six meters in range. As a result, the second and third peaks in the original profile have wrapped around so that they appear first in the profile, whereas the first peak in the original profile appears last.

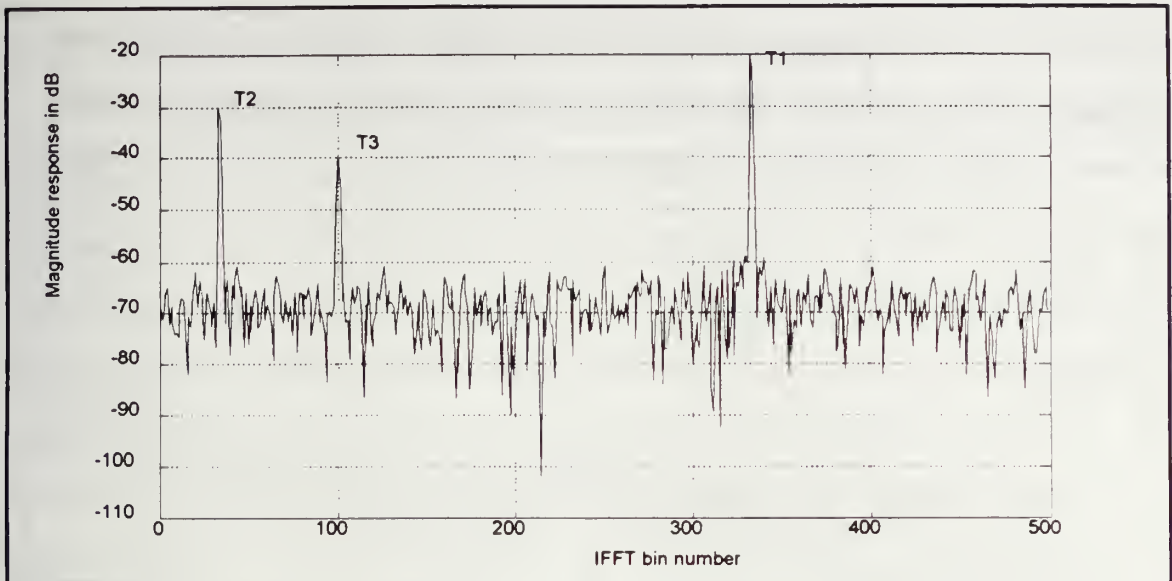


Figure 4.3 HRR Profile of three stationary targets in white noise. The range of each target has increased by 6 meters.

3. Effect of Varying the Frequency Step Size

The frequency step size determines not only the range resolution, but also the size of the unambiguous range window. A larger value of ΔF results in increased range resolution and a smaller unambiguous range window. Figure 4.4a shows the effect of increasing the step size to 20 MHz. The unambiguous range has been reduced to 7.5 meters, and the range resolution was increased to 0.015 m. Therefore, the peaks at initial ranges of 1210 m, and 1212 m have been folded over. The third peak is not resolvable because its relative location is now very close to the sidelobes of the largest peak. This figure indicates a situation in which the unambiguous range window is smaller than the original range bin width of $c\tau/2$, due to undersampling in the frequency domain.

500 x 0.015
7.5

Figure 4.4b shows the opposite situation, in which the frequency step size has been reduced to 5 MHz. In this case, the range resolution decreases to 0.06 m, but the width of the unambiguous range window increases to 30 m. This figure indicates oversampling in the frequency domain, because the entire contents of one original range

cell of width $c\tau/2$ are contained in the first half of the window. The second half represents a free region clear of any targets and possible clutter, and contains only background noise.

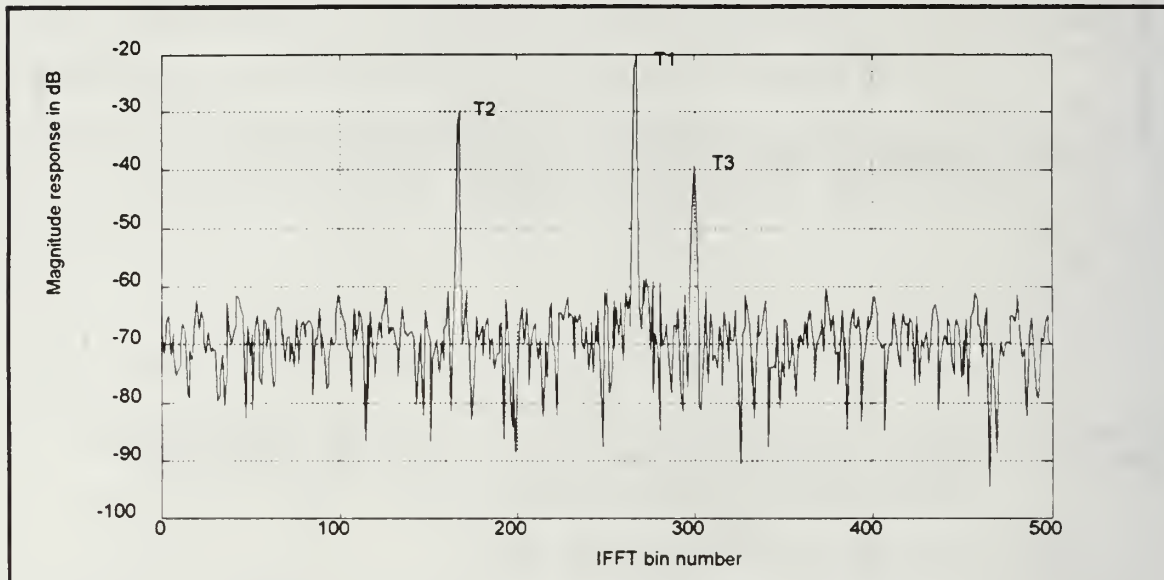


Figure 4.4a HRR Profile with of three stationary targets in white noise. $\Delta F = 20$ MHz. $R_u = 7.5$ m. The second and third peaks have folded over.

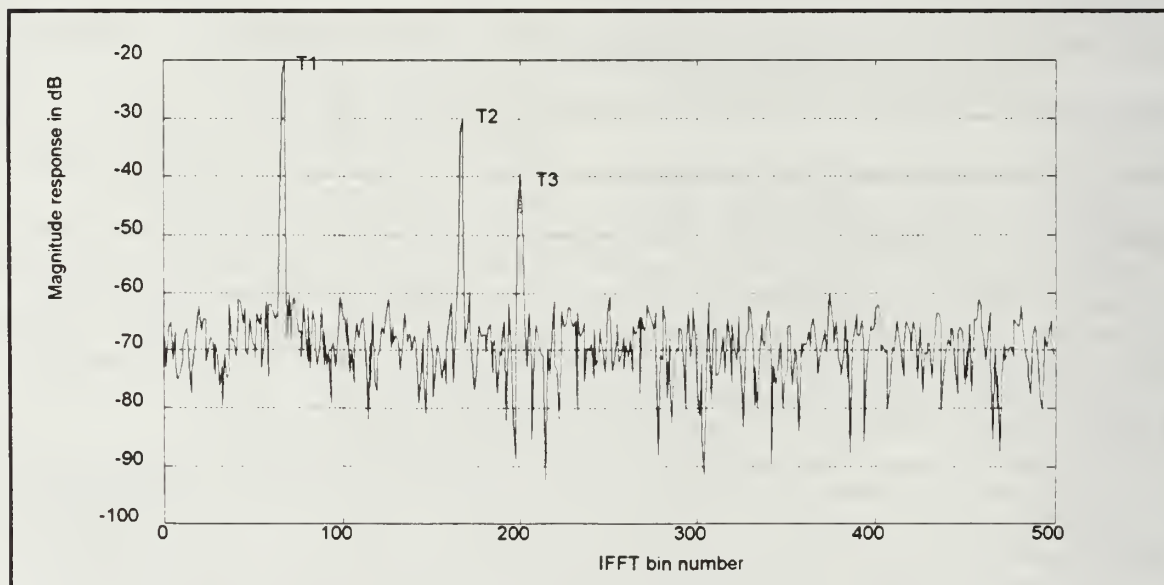


Figure 4.4b HRR Profile of three stationary targets in white noise with $\Delta F = 5$ MHz. $R_u = 30$ m. The entire contents of one original range bin now comprise one half of the unambiguous range window.

4. Effect of Varying the PRF and the Carrier Frequency

For stationary targets, the pulse repetition frequency (PRF) has no effect on the final HRR profile. However, dispersion and bin shifting of profiles are sensitive to PRF, and these only occur if the target has non-zero radial velocity. In addition, changing the nominal carrier frequency, f_c , has no effect on the range profile of stationary scatterers. Figure 4.5 shows the HRR profile for three stationary targets when the PRF is increased to 200 kHz, and Figure 4.6 shows the range profile for a carrier frequency of 12 GHz.

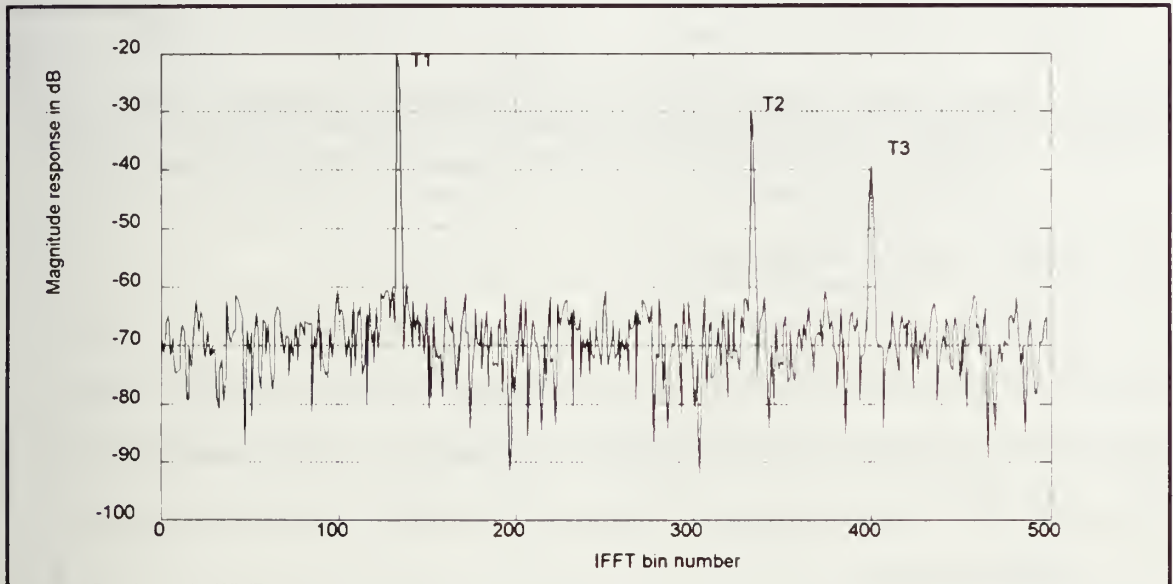


Figure 4.5 HRR Profile of three stationary targets in white noise. PRF = 200 kHz. This figure is identical with Figure 4.1 which displays the results with a PRF of 50 kHz.

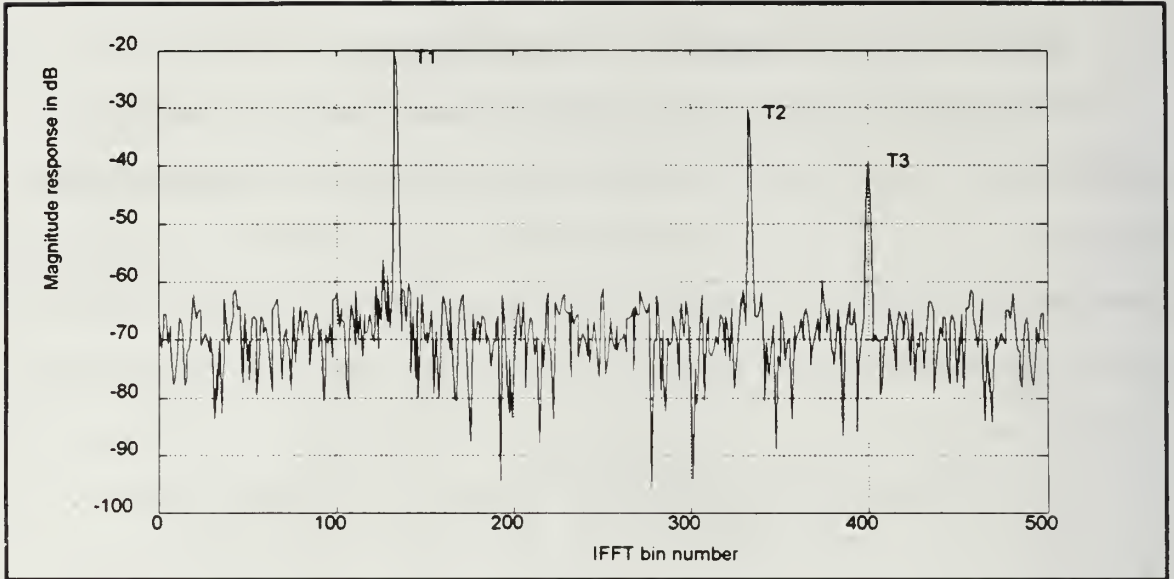


Figure 4.6 HRR Profile of three stationary targets in white noise with carrier frequency set to 12 GHz. The results are nearly identical with Figure (4.1) which showed the results for a carrier frequency of 1 GHz.

5. Effect of Range Weighting Function

Generation of HRR profiles for a given scatterer via the step frequency waveform will result in range sidelobes which can degrade the ability to detect a target in close proximity to another target. The inverse FFT results in a $\sin(x)/x$ shape for each scatterer peak which results in a peak sidelobe level of -13 dB (-43 dB for Hamming [Ref. 3:p. 426]) below the main lobe. The application of a range weighting function prior to taking the inverse FFT will result in reduced peak sidelobe level. The reduction of sidelobe levels comes at the expense of a slight reduction in the peak signal level and a reduction in range resolution due to a broadening of the main peak [Ref. 6:pp. 246-249]. The reduction in resolution is characterized by a dimensionless parameter, K , which appears in the expression for the processed range resolution, equation (2.3). Figure 4.7a shows an HRR range profile without a weighting function whereas Figure 4.7b shows the same profile multiplied by a Hamming window. The range resolution for the unweighted profile is 0.03 m as compared to 0.039 m for the windowed profile.

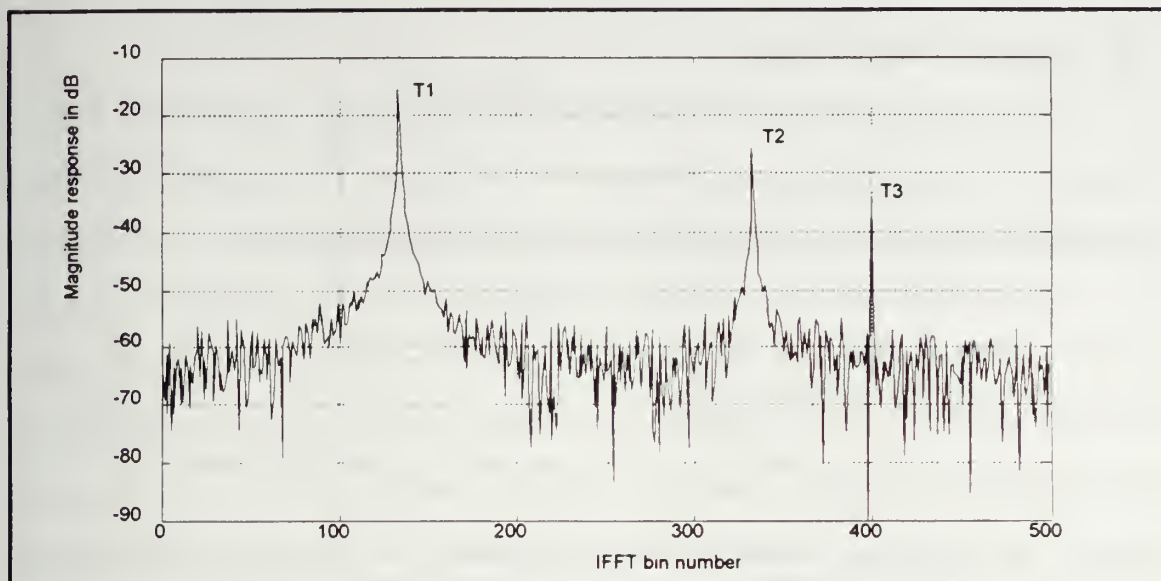


Figure 4.7a HRR Profile of three stationary targets in white noise (unwindowed).

3.93
4.07

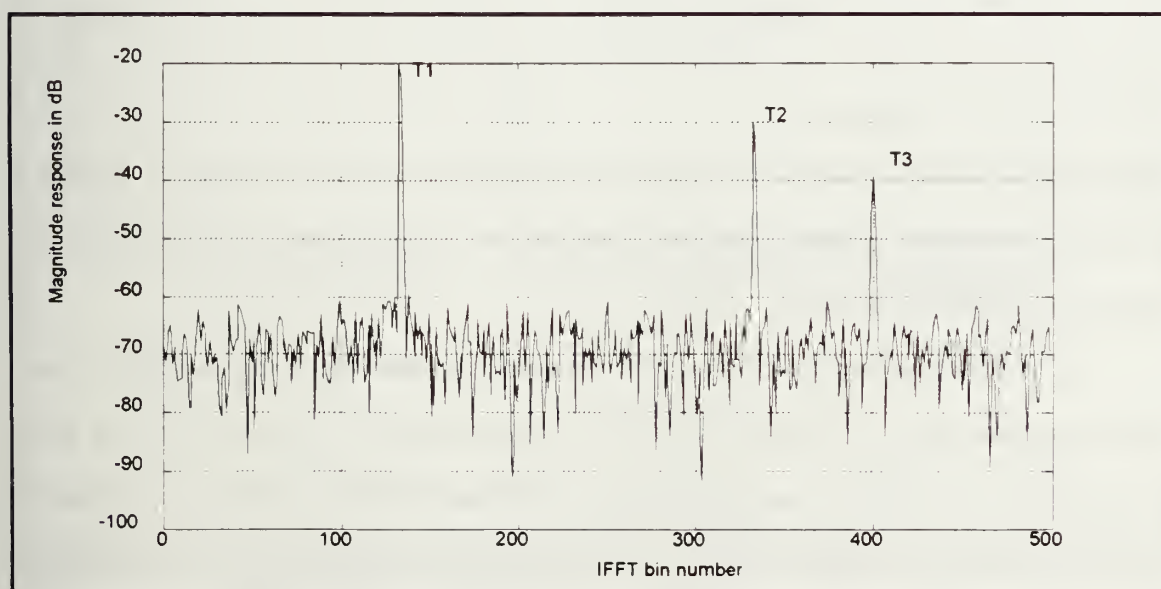


Figure 4.7b HRR Profile of three stationary targets in white noise preweighted by a Hamming window prior to taking the inverse FFT.

6. Effect of Target Velocity

Target motion degrades the resolution of the HRR profile in three ways. First, the target peak is broadened into several range bins. The number of processed range bins that the dispersed peak occupies is equal to the dispersion factor P given by

$$P = \frac{Nv}{f_{\text{PRF}} \Delta r} \quad (4.3)$$

Moreover, the dispersion of a target peak will also result in a reduction in SNR. An extremely broad target peak will also reduce the detectability of other close-in targets. Finally, target motion will lead to a shift in the target peak location. The number of bins shifted is equal to the bin shift factor L given by

$$L = \left(\frac{\hat{f}_c}{B_{\text{eff}}} \right) \frac{Nv}{f_{\text{PRF}} \Delta r} \quad (4.4)$$

If the bin shift factor L exceeds the difference between the number of pulses N and the IFFT bin location for a corresponding stationary target, the target peak will wrap around resulting in an aliased profile.

The effects of target motion can be mitigated by either increasing the PRF or by velocity compensation. An increase in the PRF will decrease the dispersion factor P and the bin shift factor L as in equations (4.3) and (4.4) respectively. Switching to a higher PRF will improve the range resolution and detectability of moving targets without requiring prior knowledge of the target velocity. However, a higher PRF results in a reduced unambiguous range (in conventional radar terms):

$$R_{\text{unamb}} = \frac{c}{2f_{\text{PRF}}} \quad (4.5)$$

Velocity compensation, on the other hand, converts the range profile of a moving target into the corresponding profile of a stationary target at the initial range location. As a result, the dispersion and bin shifting are completely canceled. However, velocity compensation requires an accurate estimate of the target velocity. If different scatterers within one pulse width have different velocities, an average of the velocities must be used, but it will not result in complete compensation for any scatterer.

a. Effect of Uncompensated Target Velocity

Figures 4.8a-d show the uncompensated HRR profile for two stationary targets and one moving target with speeds of 100 m/s, 300 m/s, 500 m/s, and -200 m/s respectively, at a PRF of 50 kHz.

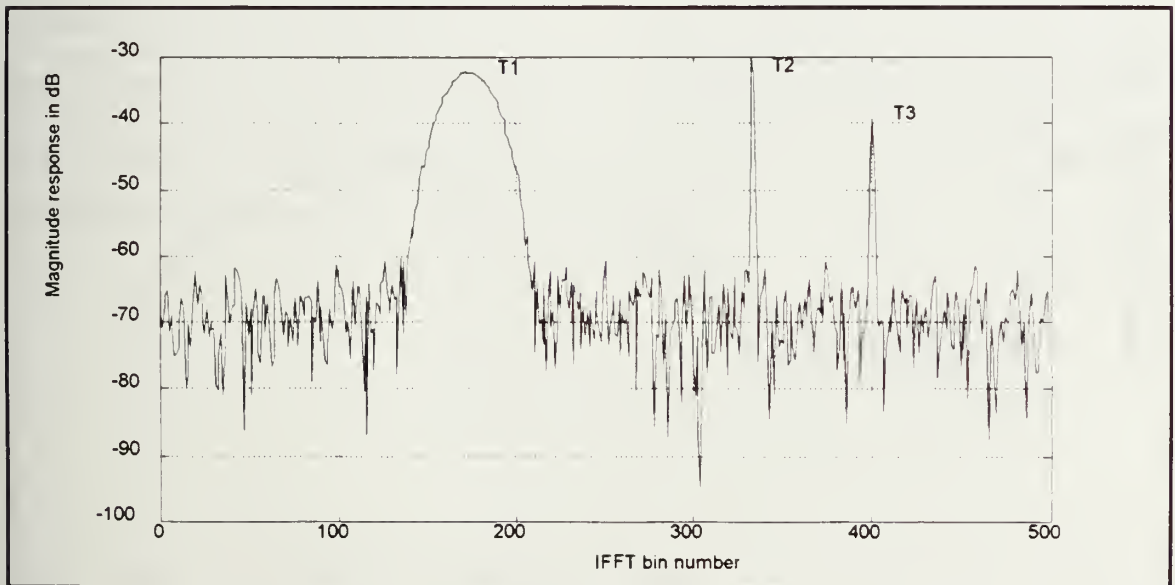


Figure 4.8a HRR Profile of one moving target, (T1) with a radial velocity of 100 m/s. PRF = 50 kHz. T2 and T3 are stationary.

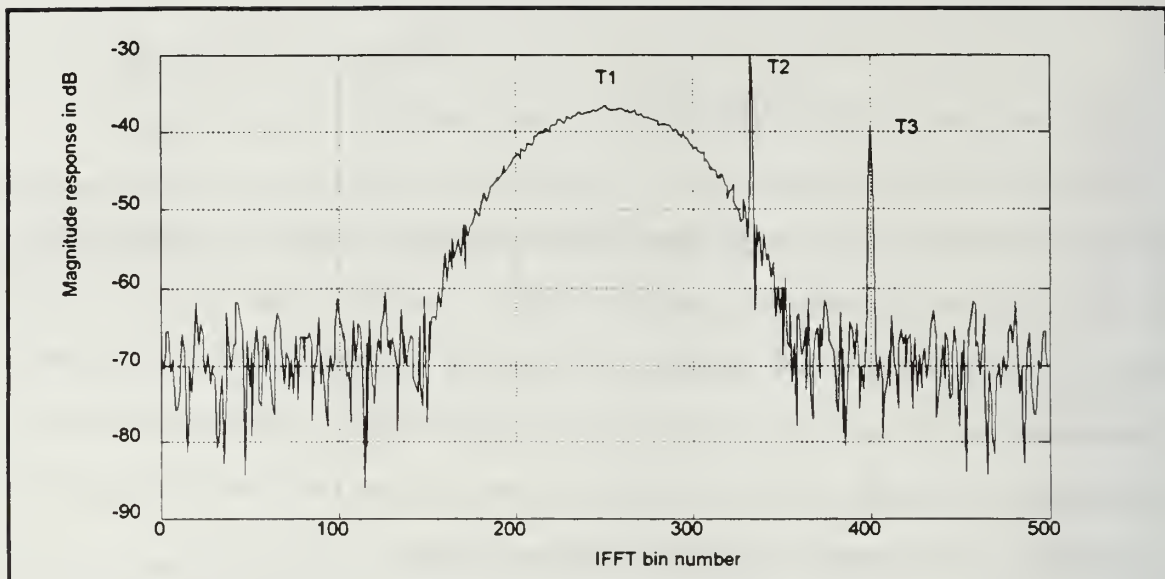


Figure 4.8b HRR Profile of one moving target, (T1) with radial velocity of 300 m/sec. PRF = 50 kHz. T2 and T3 are stationary.

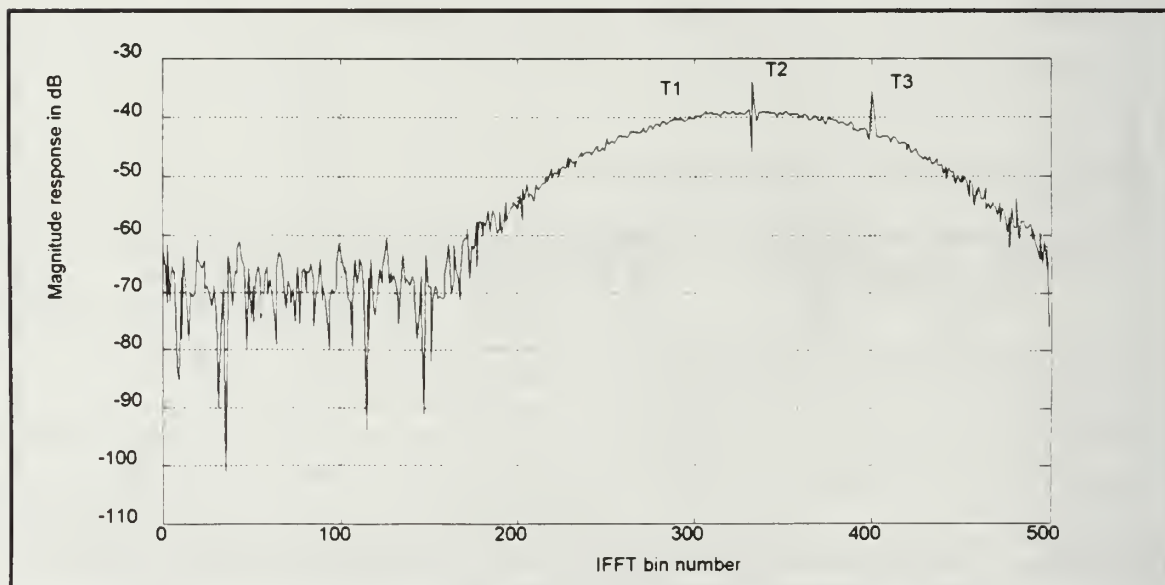


Figure 4.8c HRR Profile of one moving target, (T1) with radial velocity of 500 m/sec. PRF = 50 kHz. T2 and T3 are stationary.

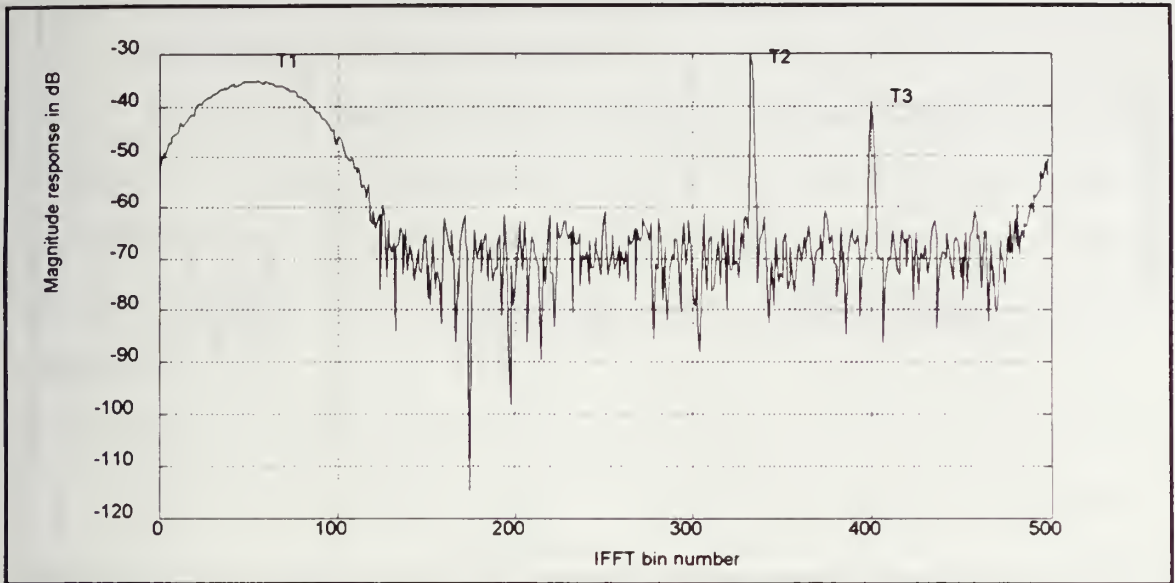


Figure 4.8d HRR Profile of one moving target, (T1) with radial velocity of -200 m/s which indicates a closing target. PRF = 50 kHz. T2 and T3 are stationary.

Figure 4.9 shows the effect of all three scatterers with different velocities with respect to the radar. This situation can exist if different regions of a target have differential velocities with respect to each other. Figure 4.10 shows the range profile if all three scatterers have the same radial velocity. The radar cross section of each moving target has been set to 10 m^2 in Figures 4.11 to 4.13 for better visual clarity in identifying the effects of multiple moving targets on the range profile.

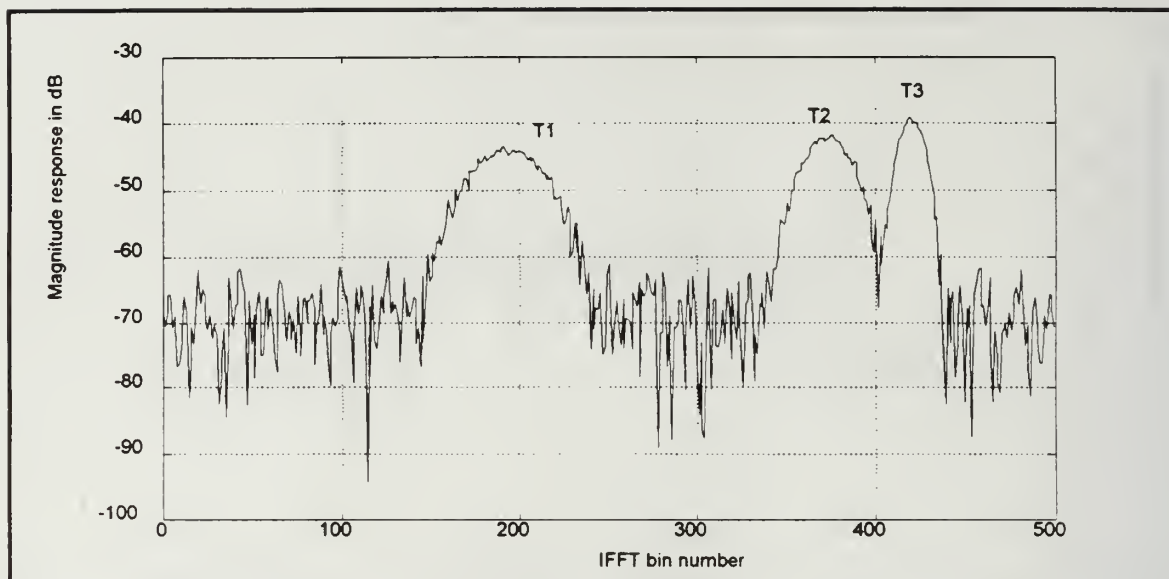


Figure 4.9 HRR Profile for three moving targets each with a different radial velocity. The radial velocities are 150 m/s (T1), 100 m/s (T2), and 50 m/s (T3). PRF = 50 kHz.

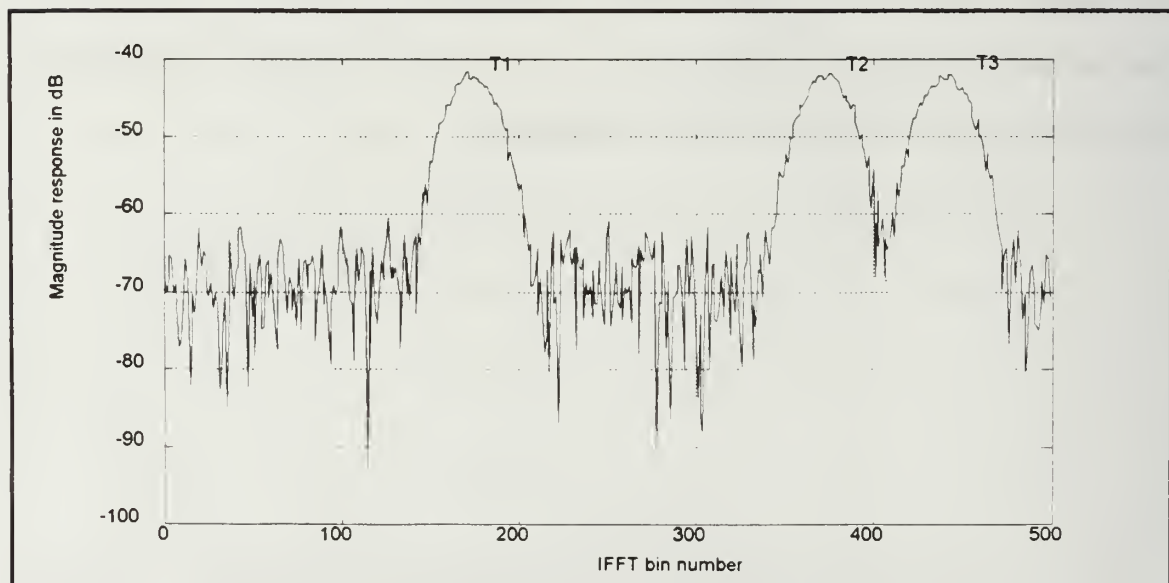


Figure 4.10 HRR Profile of three targets each with a radial velocity of 100 m/sec. PRF = 50 kHz.

b. Effect of Velocity Compensation

Velocity compensation at a speed of 100 m/sec can be applied to the profile in Figure 4.10 to enhance its range resolution whereas the same compensation factor will not achieve optimum results for Figure 4.9 which has different radial velocities. Figures 4.11 and 4.12 display the results of velocity compensation applied to Figures 4.9 and 4.10 respectively.

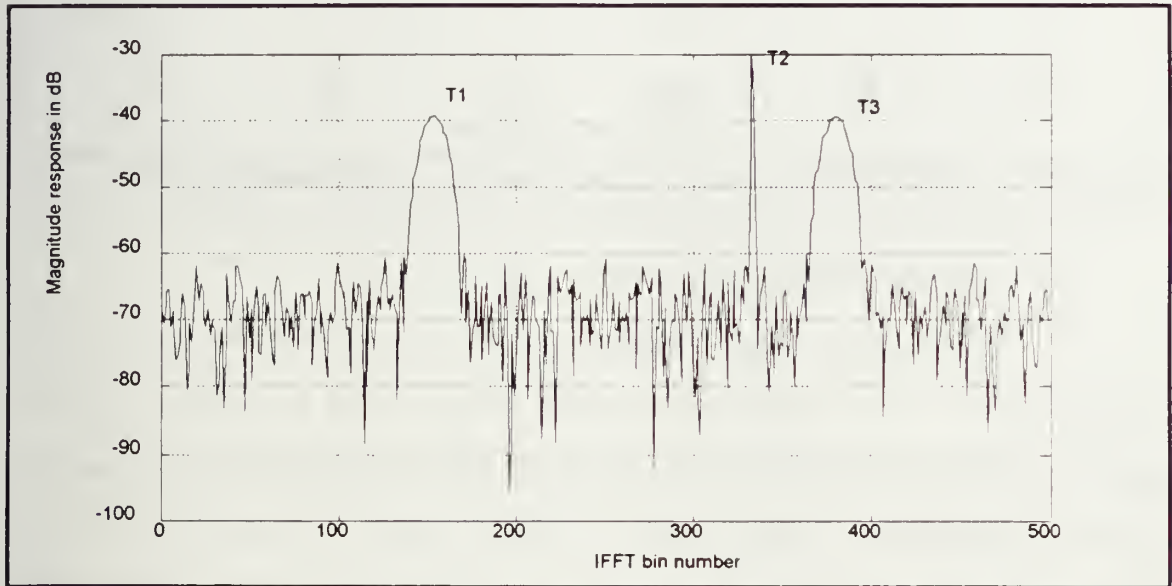


Figure 4.11 HRR Profile in Figure (4.9) with velocity compensation of 100 m/s. Note that T2 (at 100 m/s) is compensated correctly, but that T1, and T3 are still dispersed due to a mismatch between the target velocity and the compensated velocity.

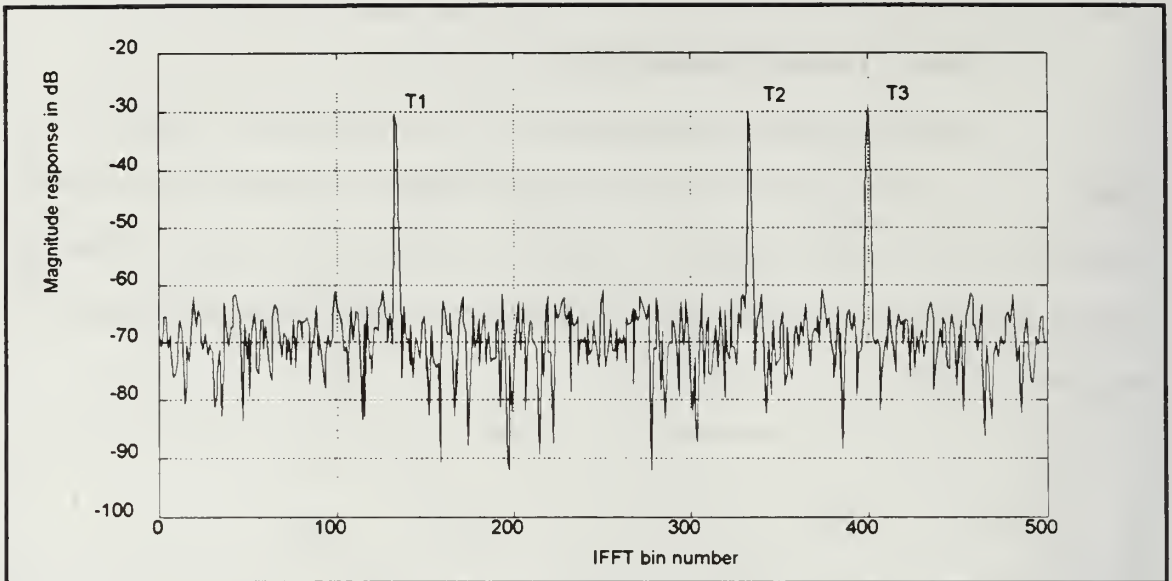


Figure 4.12 HRR Profile of Figure (4.10) with velocity compensation of 100 m/s. Note, that the original distortion free range profile is recovered.

c. Effect of Increasing the PRF

The major limitation of applying velocity compensation factors is that an accurate estimate of the velocities of individual scatterers must be obtained a priori. Moreover, differential velocities between scatterers within a single target will result in imperfect compensation if a single velocity correction is applied, as shown in Figure 4.11. As a result, the PRF should be increased as much as possible within other design constraints to reduce the negative impact of radial velocity on the range profile. As the PRF is increased, the velocity correction becomes less stringent. Figures 4.13a-c show the effect of varying the PRF from 20 kHz to 100 kHz, and 250 kHz respectively for three scatterers each having a radial velocity of 100 m/s. *more unamb loca in range afford*

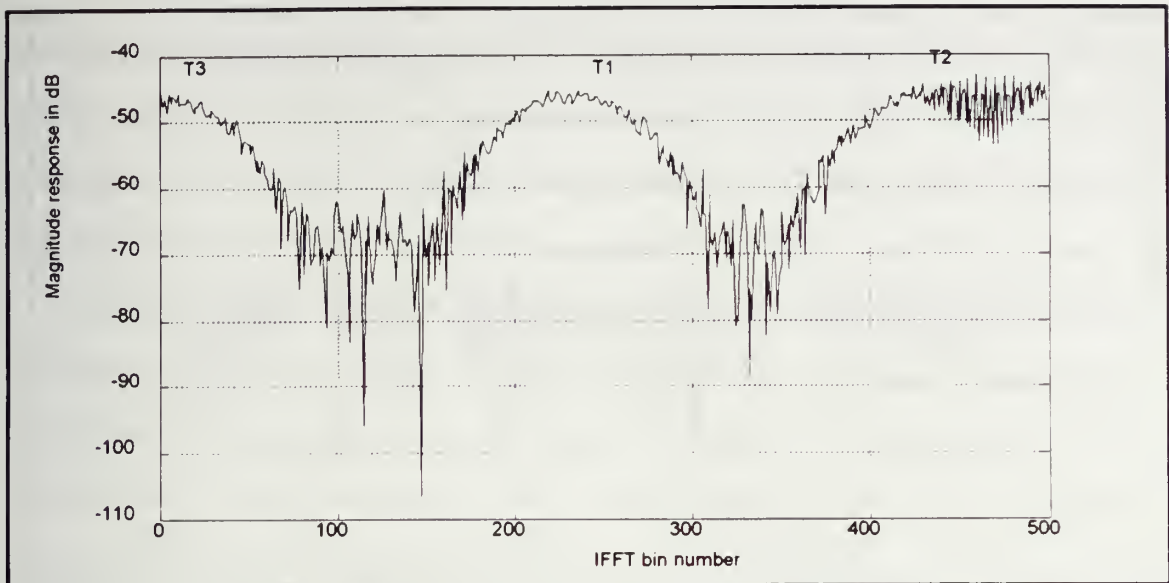


Figure 4.13a HRR Profile of three moving targets with a radial velocity of 100 m/sec. PRF = 20 kHz. Note the increased dispersion and bin shift of all targets, and the aliasing caused by the wraparound of the target peak (T3).

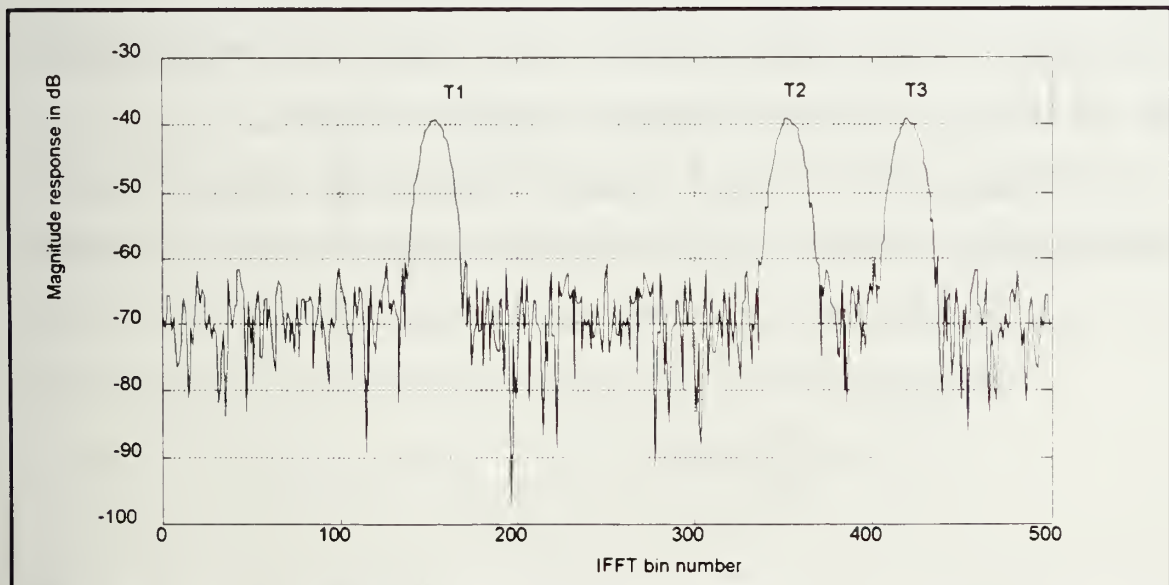


Figure 4.13b HRR Profile of three targets with a radial velocity of 100 m/sec. PRF = 100 kHz. Note the reduction in dispersion and bin shifting.

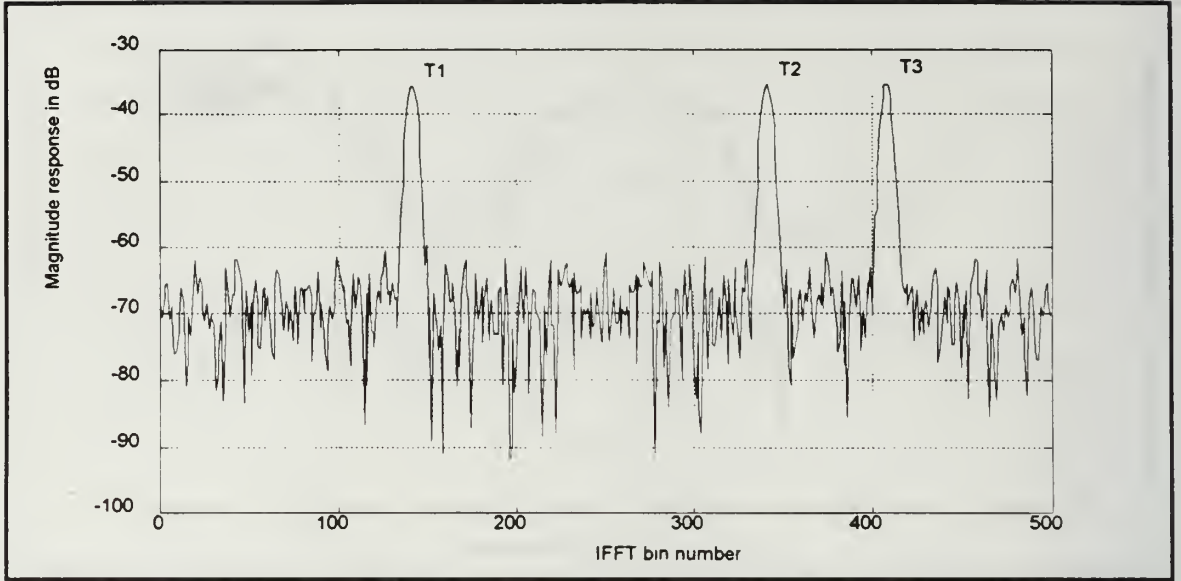


Figure 4.13c HRR Profile of three scatterers with radial velocity of 100 m/s. PRF = 250 kHz. Note that this profile looks similar to the velocity compensated profile.

B. HRR PROFILES IN CLUTTER LIMITED SITUATIONS

If echo returns from clutter are present in the original range cell, then the appearance of the HRR profile changes dramatically. The processed range profile contains numerous peaks due to clutter as well as a few peaks due to the targets of interest.

By keeping the product of $\tau\Delta F < 1$, the clutter filled range cell occupies only a small percentage of the unambiguous range window depending upon the value of $\tau\Delta F$ as given by:

$$\frac{c\tau/2}{R_u} = \tau\Delta F \quad (4.6)$$

The remainder of the range window consists of a clutter-free region containing only thermal noise. Targets having sufficient radial velocity in the line of sight of the radar will

have their peaks shifted from the clutter filled region to the clutter-free region of the range profile where it will be easy to detect them. The extent to which the moving target migrates into the clutter-free region depends on the parameters which determine the dispersion factor P and the bin shift factor L as given by equations (4.3) and (4.4).

Application of velocity compensation in a clutter limited situation without clutter cancellation is counterproductive since the compensation factor causes the target peak to move back into the clutter region. Although the dispersion of the target peak results in a loss of resolution, the moving target will be detected whereas the corresponding stationary target must compete with the clutter return in order to be detected.

The HRR profile of three scatterers within a single original range cell in the presence of clutter is simulated by adding several stationary peaks to represent the clutter. The nominal value of $\tau\Delta F$ is chosen to be 0.1. Therefore, the clutter region of the range profile comprises ten percent of the unambiguous range window. The signal to clutter ratio (SCR) is the ratio of the signal power to the clutter power at the input of the signal processing unit for a 1 m^2 target. The clutter magnitude is also based on the amplitude of a 1 m^2 target. The SCR can be specified independent of the SNR by the user. The full description of the simulation program is listed in Appendix A. The parameters for the reference HRR profile with clutter are shown in Table 4.2. The corresponding profile is displayed in Figure 4.14. Unless mentioned otherwise, all other parameters except the parameter of interest will have the same value as shown in the reference profile.

TABLE 4.2 REFERENCE PARAMETERS FOR HRR PROFILE WITH CLUTTER

Parameter	Reference Value
Number of Pulses (N)	500
Frequency Step Size (ΔF)	1 MHz
Pulse Repetition Frequency (PRF)	20 kHz
Pulse Width (τ)	0.1 μ sec
Nominal Carrier Frequency (f_o)	1 GHz
Unambiguous Range Window (R_u)	150 m
Range Weighting Function	Hamming (K=1.33)
Initial Target Ranges	1204 m (T1), 1208 m (T2), 1212 m (T3)
Target Cross Sections	100 m ² (T1), 10 m ² (T2), 1 m ² (T3)
Target SCR ratio	0 dB (T1), -10 dB (T2), -20 dB (T3)
Target SNR	20 dB (T1), 10 dB (T2), 0 dB (T3)
Target Velocities	0 m/s (T1), 0 m/s (T2), 0 m/s (T3)

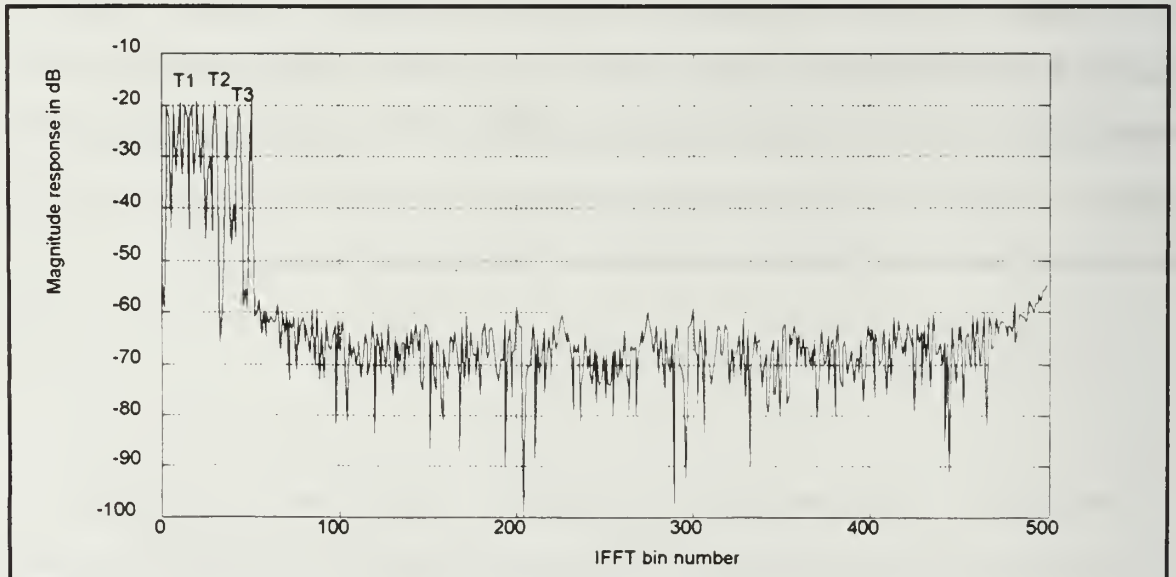


Figure 4.14 Reference HRR Profile for three stationary targets in clutter.

Due to clutter in the original range bin, only the two larger stationary targets are above the clutter. The clutter region comprises a total of $(\tau\Delta F)N$ bins, which in this case equals 50.

1. Effect of Varying the Number of Pulses

An increase in the number of pulses, N , results in increased range resolution compared to the resolution of 0.3 m (unwindowed) for Figure 4.14. The effects of increasing the number of pulses to 1000 and reducing the number of pulses to 250 are shown in Figure 4.15a, and Figure 4.15b respectively.

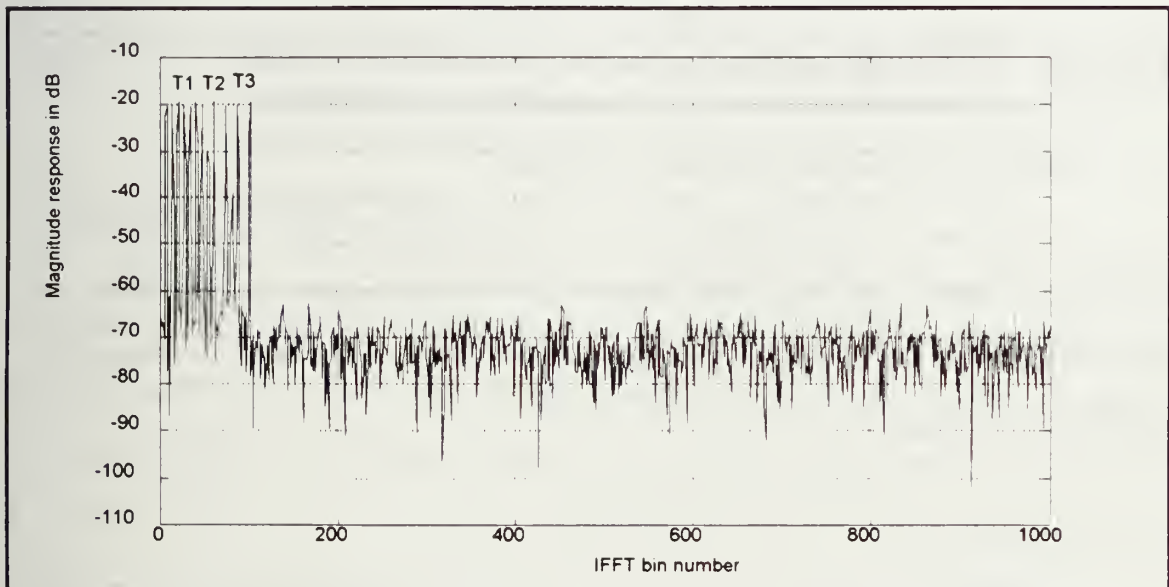


Figure 4.15a HRR Profile for three stationary targets in clutter. $N = 1000$.
Note the increased range resolution of 0.15 m (unwindowed).

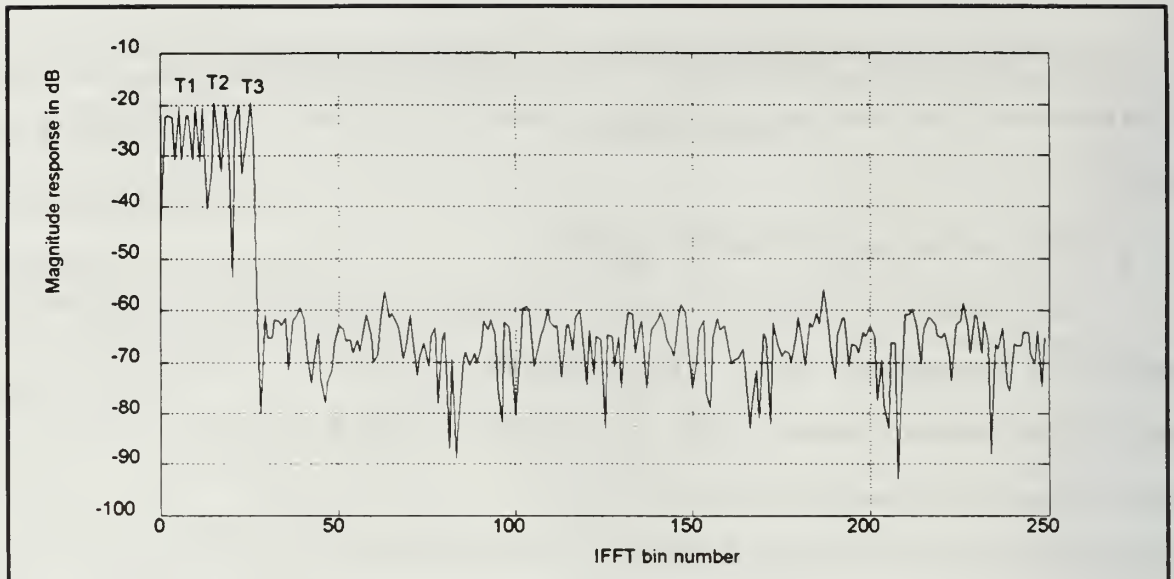


Figure 4.15b HRR Profile for three stationary targets in clutter. $N = 250$.
Note the reduction in range resolution (0.6 m unwindowed).

2. Effect of Varying the Frequency Step Size

An increase in the frequency step size also results in finer range resolution. However, the clutter occupies a larger fraction of the unambiguous range window as shown in Figure 4.16. As a result, there is less clutter free space with which to distinguish between moving targets.

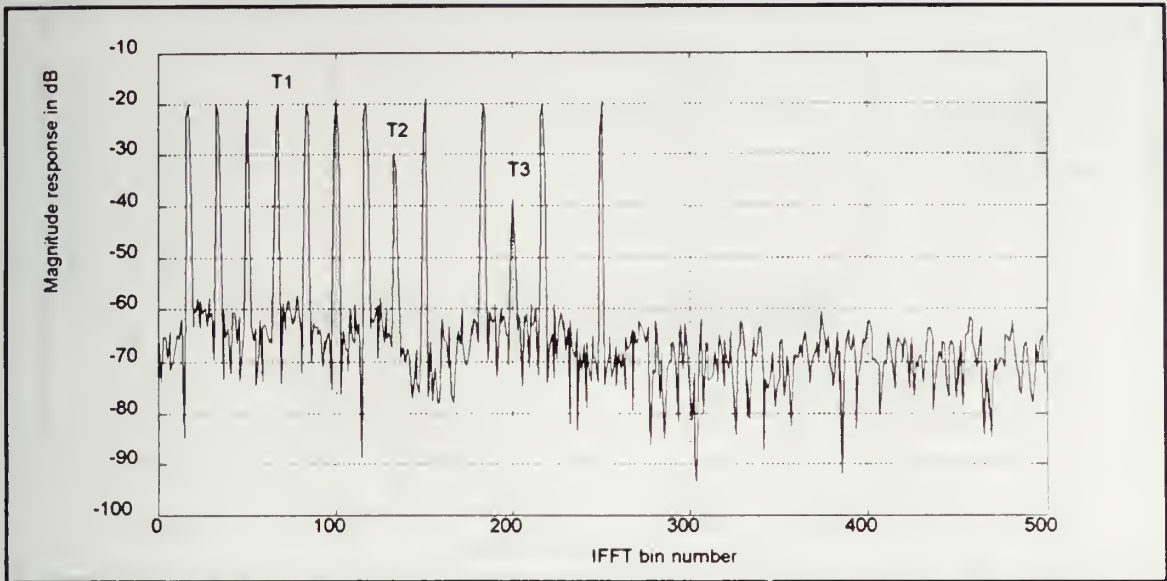


Figure 4.16 HRR Profile of three stationary targets in clutter. $\Delta F = 5$ MHz, range resolution = 0.06 m (unwindowed). Note that the clutter occupies half of the unambiguous range window.

3. Effect of Target Velocity

In a clutter limited situation, targets with sufficient velocity will migrate into the clutter free region. Assuming that the number of pulses N is held fixed to maintain the required range resolution, the PRF primarily determines the extent to which the target moves into the clutter free region. As given by equations (4.3) and (4.4), the dispersion factor and bin shift factor are inversely proportional to the PRF. Thus for a given target velocity, a lower PRF will shift the target peak further into the clutter free region.

a. Effect of Single Moving Target

The effects of velocity changes for the 100 m^2 target (T1) are displayed in Figures 4.17a-d. The increase in radial velocity from 300 m/s to 1000 m/s results in both increased dispersion of the scatterer peak as well as an increased amount of bin shifting of the profile. An incoming target, as shown in Figure 4.17d shows the same effects except that the bin shift will be in the opposite direction

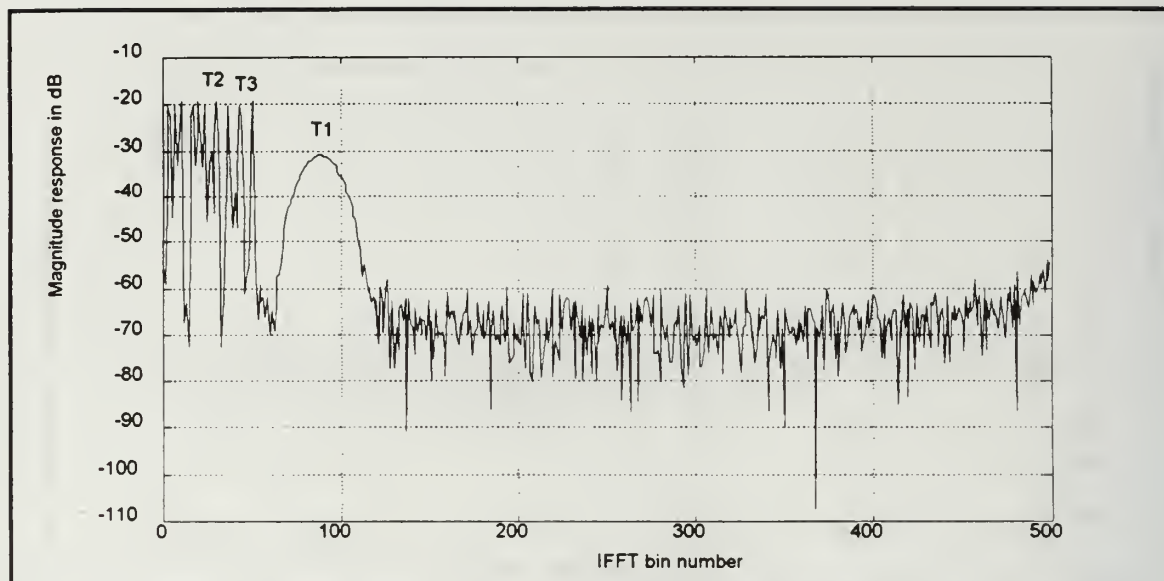


Figure 4.17a HRR Profile of moving target (T1) in clutter. Radial velocity = 300 m/s.

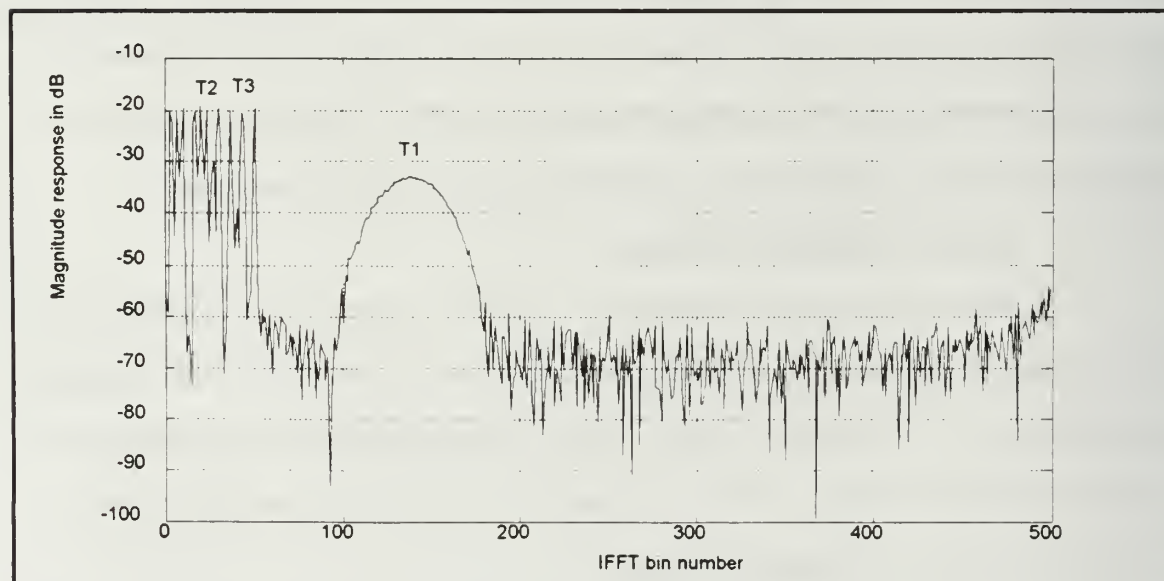


Figure 4.17b HRR Profile of moving target (T1) in clutter. Radial velocity = 500 m/s.

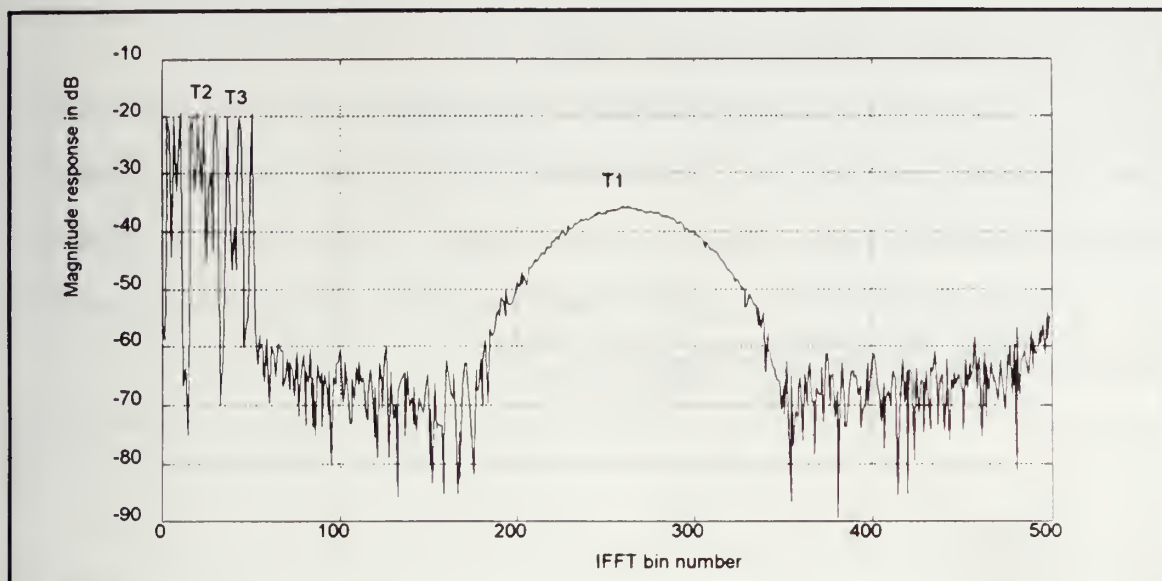


Figure 4.17c HRR Profile of moving target (T1) in clutter. Radial velocity = 1000 m/s

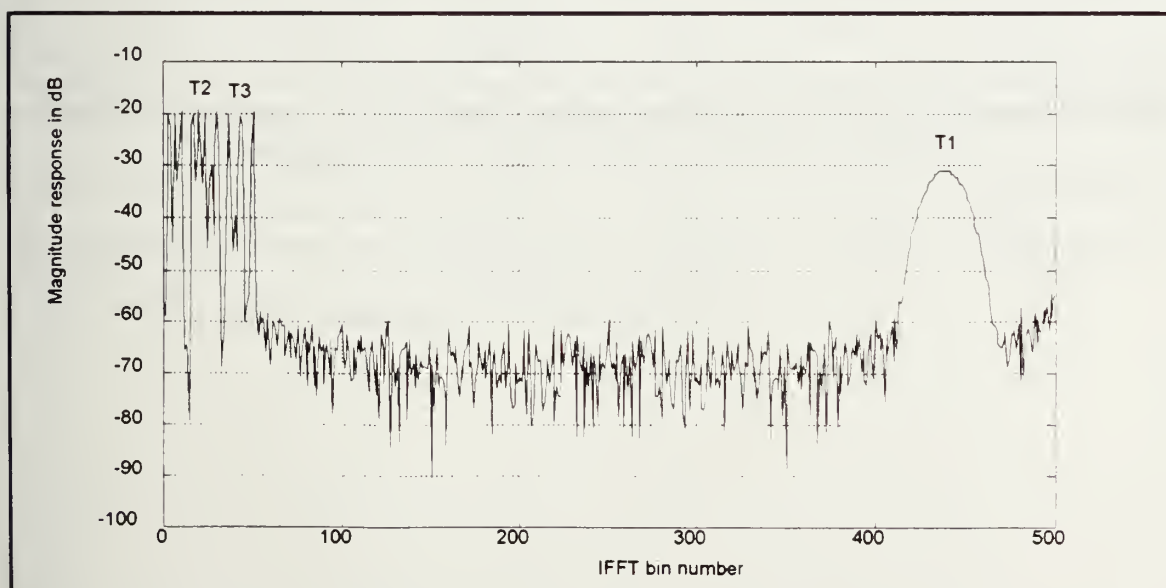


Figure 4.17d HRR Profile of moving target (T1) in clutter. Radial velocity = -300 m/s which indicates a closing target.

b. Effect of Multiple Moving Targets

The effects of having multiple moving targets with the same velocity are shown in Figures 4.18a and (4.18b). This situation could correspond to multiple scatterers within one distributed target traveling at the same velocity. As the velocity is increased from 100 m/s to 500 m/s, the dispersed target peaks merge into each other making individual target detection nearly impossible.

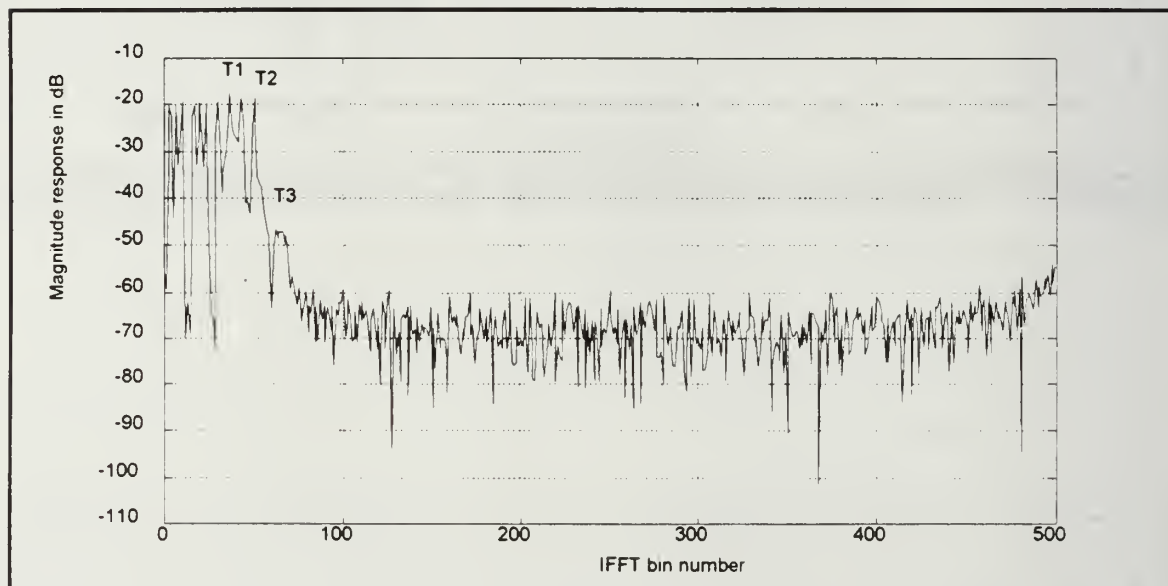


Figure 4.18a HRR Profile of three moving targets in clutter. Radial velocity = 100 m/s. Note that each dispersed, shifted target peak is distinguishable.

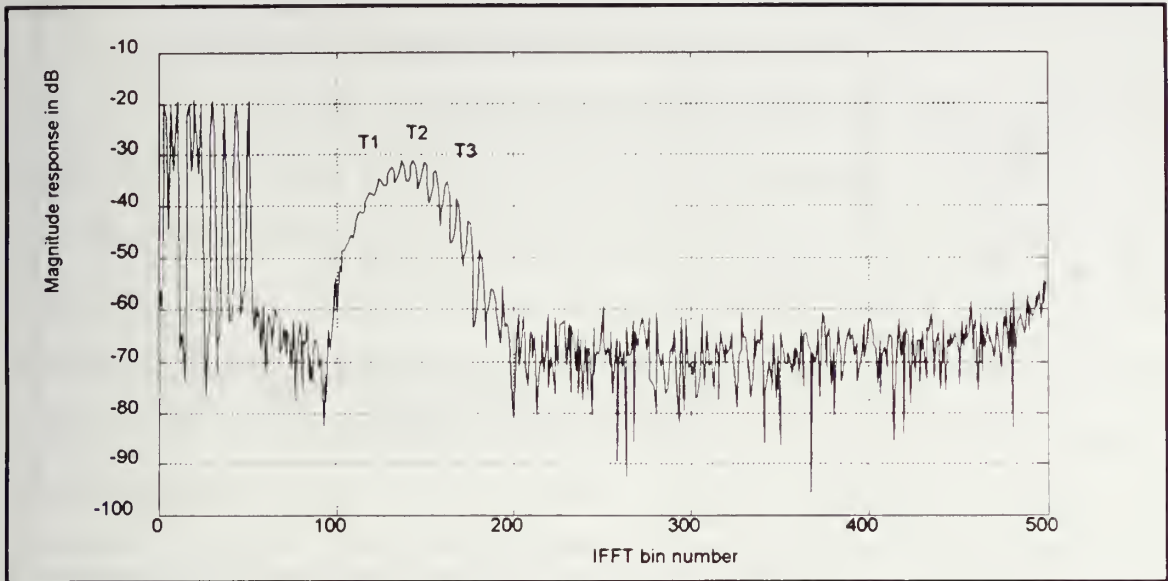


Figure 4.18b HRR Profile of three moving targets in clutter. Radial velocity = 500 m/s. Note the merging of the target peaks into one large peak.

The effects of multiple moving targets with different velocities on the range profile are presented in Figures 4.19a, and (4.19b). This situation can indicate relative motion between different scattering centers within a larger distributed target or closely spaced distinct targets. As shown in Figure 4.19b, it is possible to mistake a fast opening target with a rapidly closing target. Therefore, moving targets in the left half of the profile should be interpreted as opening targets (negative Doppler), and targets in the right half should be viewed as closing targets (positive Doppler.) In both cases, the magnitude of the Doppler shift increases as the targets approach the center. The sign convention is the opposite of that used in conventional pulse-doppler radars.

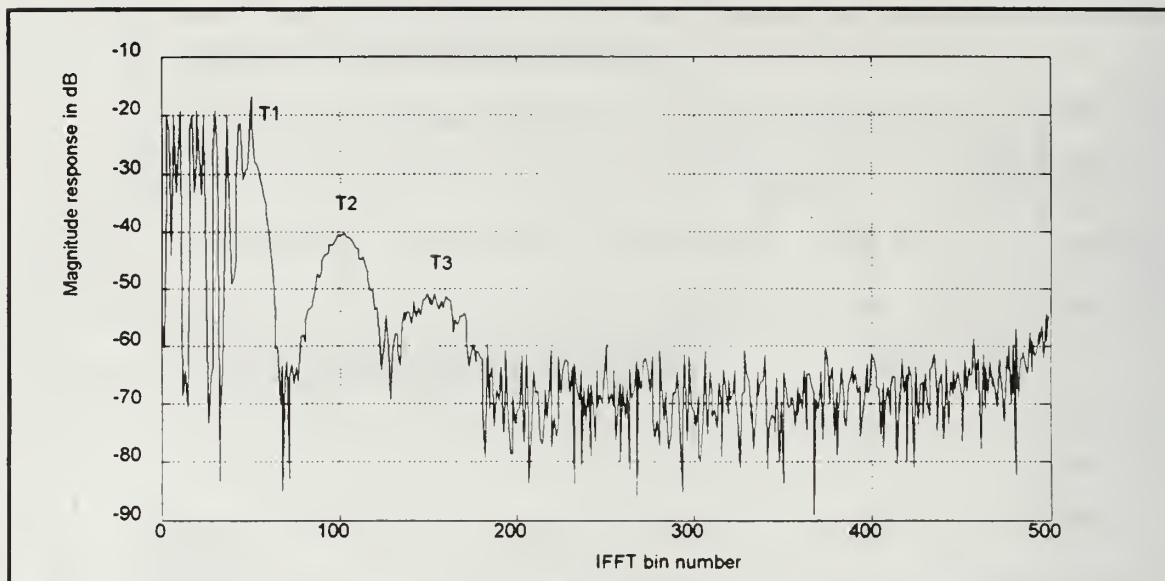


Figure 4.19a HRR Profile of three moving targets in clutter. Radial velocities for T1, T2, and T3 are 150 m/s, 300 m/s and 450 m/s respectively.

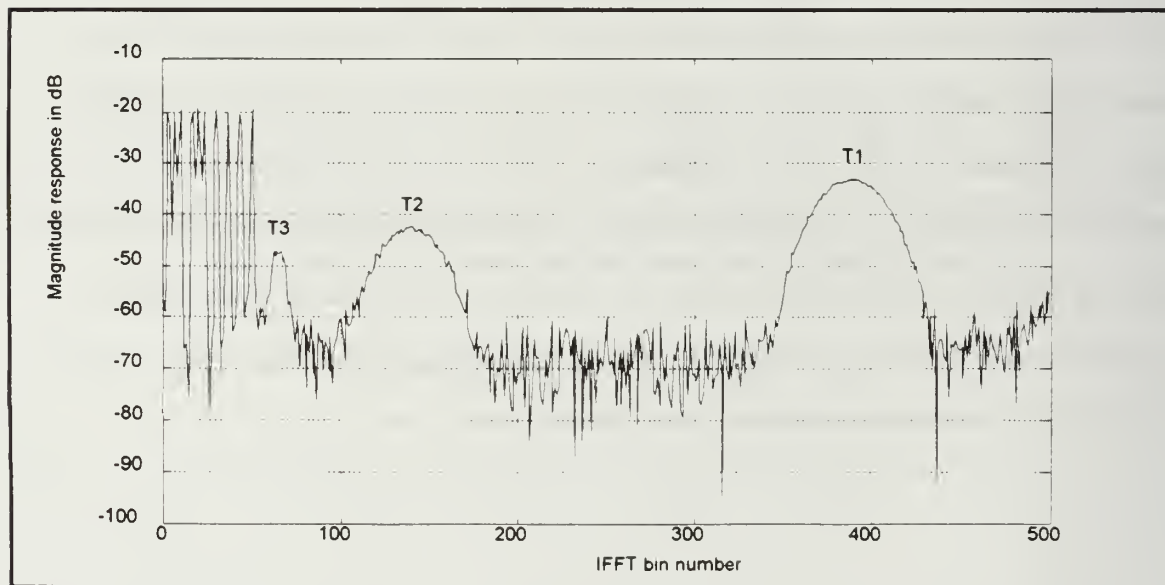


Figure 4.19b HRR Profile of three moving targets in clutter. T1 is an incoming target with a radial velocity of -500 m/s, T2 has a radial velocity of 450 m/s, and T3 has a radial velocity of 100 m/s. Since T1 and T2 have nearly opposite velocities, it is possible to mistake a fast opening target (T2), for a fast closing target (T1).

c. Effect of Varying the PRF

The effects of varying the radar's pulse repetition frequency are shown in Figures 4.20a-c for PRF's of 5 kHz, 20 kHz, and 200 kHz respectively for three targets with velocities of 150 m/s, 300 m/s, and 450 m/s. For these plots, the cross sections of all targets have been set at 10 m^2 to focus solely on the effects of varying the PRF. For the low PRF case, the bin shift and dispersion of the third target result in fold over of the peak, resulting in an aliased profile. As the PRF is increased to 200 kHz, the peaks broaden slightly but remain in the clutter region.

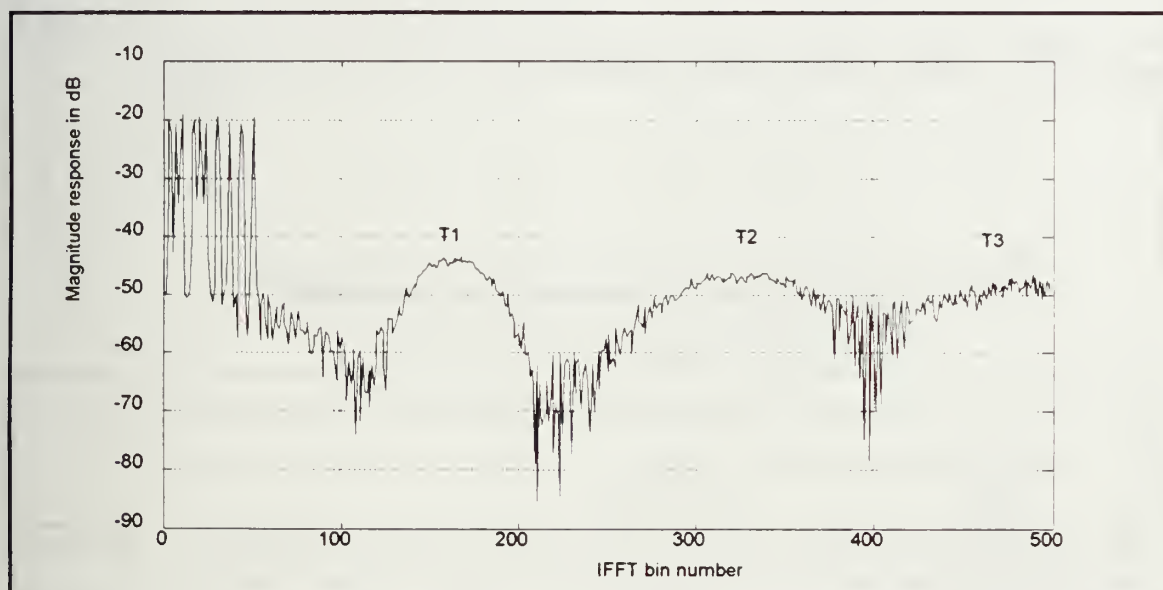


Figure 4.20a HRR Profile of three moving targets in clutter. PRF = 5 kHz. Note the increased bin shift and dispersion of the target peaks and the foldover of the third target.

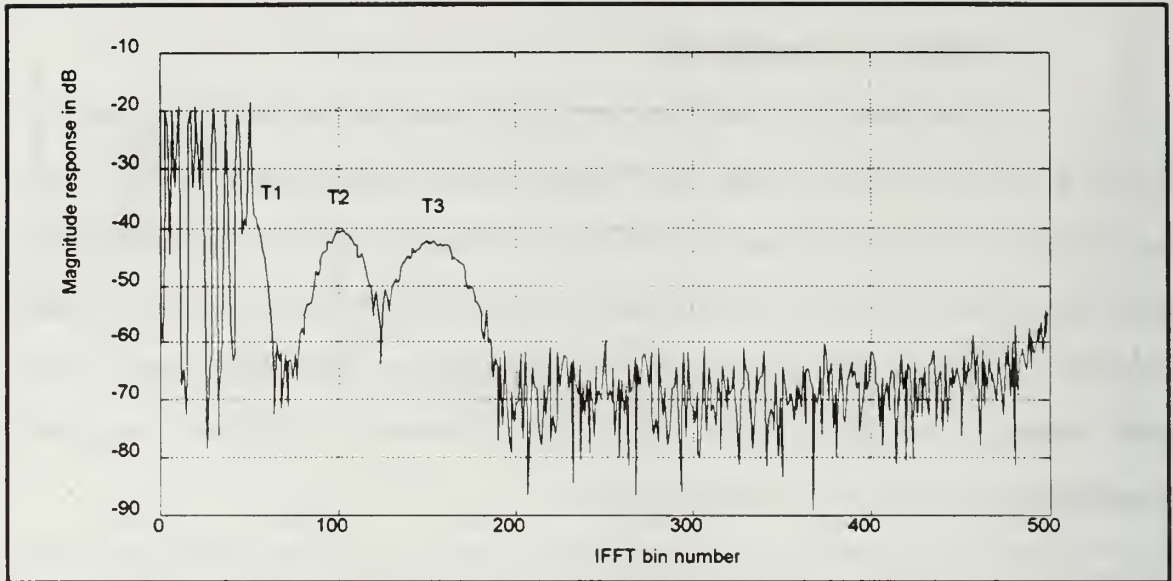


Figure 4.20b HRR Profile of three moving targets in clutter. PRF = 20 kHz.

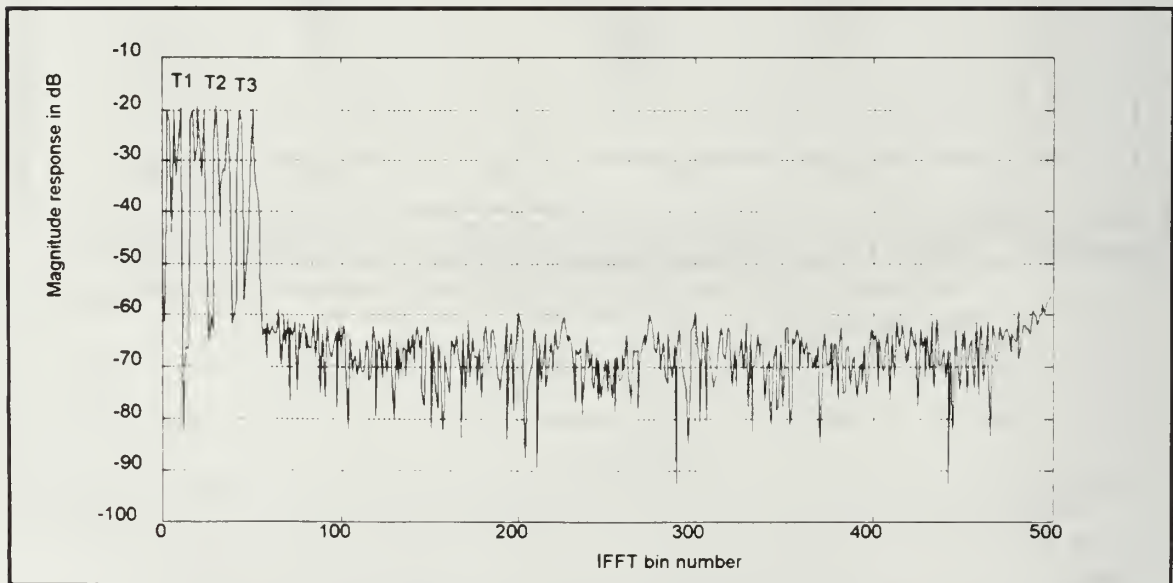


Figure 4.20c HRR Profile of three moving targets in clutter. PRF = 200 kHz.
Note that all three targets are still in the clutter due to the high PRF.

Finally, velocity compensation cannot be applied to moving targets if clutter is present in the original range cell. Applying a compensation factor will eliminate the dispersion of the peak resulting in increased range resolution. However, unless the clutter is canceled, the compensation will shift the target peak back into the clutter. Figure 4.21 shows the effect of velocity compensation for three moving targets each with a radial velocity of 100 m/s at a PRF of 20 kHz. As a result of the compensation, each of the targets have shifted back into the clutter region and are less detectable.

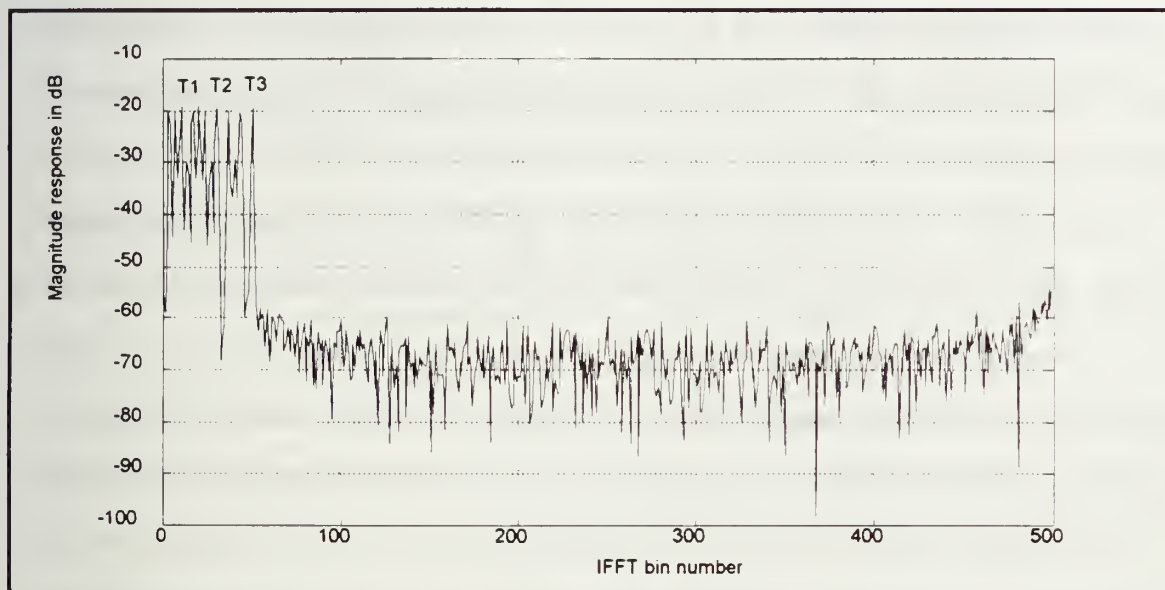


Figure 4.21 HRR Profile of three moving targets in clutter. Radial velocity = 100 m/s. for each target. Velocity compensation of 100 m/s has been applied to the profile. Note that the targets have shifted back into the clutter.

C. IMPROVING RESOLUTION OF MOVING TARGETS BY CLUTTER CANCELLATION AND VELOCITY COMPENSATION

The range profiles of moving targets in clutter are clearly visible only if the target has sufficient velocity to migrate to the clutter free region. Although the target peak will be easily detected once in the clutter free zone, the resulting resolution will be poorer due to dispersion. The dispersion factor P given in equation (4.3) determines the number of processed range bins occupied by the moving target. The effective processed resolution of the target equals $P\Delta r$ instead of the optimum value of Δr . In addition to the loss of resolution, an excessive shift in the peak location due to range-doppler coupling may result in target wrap around. The number of bins shifted is equal to the bin shift factor L , given in equation (4.4).

To overcome these drawbacks one could apply velocity compensation directly. However, this would only shift the target peak back into the clutter. Therefore, the clutter must be canceled prior to applying the velocity compensation. One method to improve the range resolution of moving targets in clutter is proposed as follows. First, the frequency domain target reflectivity data is converted to the time domain HRR profile by an inverse FFT. The frequency domain data is not windowed prior to the IFFT. The clutter filled region of the range profile is canceled by multiplication with a rectangular gating function. The modified range profile is then windowed prior to being transformed into frequency domain data via the FFT. The velocity compensation factor is applied to the frequency domain data, and the resulting data is transformed to the corrected range profile by an inverse FFT. The steps are summarized below:

1. Convert frequency domain reflectivity data to the initial HRR profile via the IFFT
2. Apply clutter cancellation to the initial HRR profile
3. Estimate the compensation velocity
4. Apply a windowing function to the initial HRR profile

5. Convert the modified HRR profile to frequency domain data via the FFT
6. Apply velocity compensation to the resulting frequency domain data
7. Convert the compensated frequency domain data to the final HRR profile by IFFT.

As a result of applying these steps, the moving target peak moves to the correct range in the HRR profile. More importantly, the resulting processed range resolution equals Δr instead of $P\Delta r$.

One key assumption in this method is that all targets within the original range bin have the same velocity. This assumption is valid in the case of several distinct scatterers originating from a large extended target. As a result, a single velocity compensation factor can be applied to the HRR profile corresponding to an original range bin. Since the target velocity is unknown, a number of different velocity compensations can be applied one at a time, and the compensation which yields the best resolution can be taken as the target velocity.

A simulation program was developed in MATLAB to demonstrate clutter cancellation with velocity compensation for a single moving target. This program requires the user to supply the IFFT bin number corresponding to the maximum extent of the clutter region, and the compensation velocity. The reference parameters for the simulation are listed in Table 4.3. A complete description of the program (HRRCAD.M) is given in Appendix A. As opposed to earlier profiles, the range profiles are given in magnitude instead of decibel units for improved visual clarity. All simulation parameters other than that which is being varied are fixed at the reference values indicated in Table 4.3.

**TABLE 4.3 REFERENCE PARAMETERS FOR HRR SIMULATION WITH
CLUTTER CANCELLATION AND VELOCITY COMPENSATION**

Parameter	Reference Value
Number of Pulses (N)	500
Frequency Step Size (ΔF)	1 MHz
Pulse Repetition Frequency (PRF)	20 kHz
Pulse Width (τ)	0.1 μ sec
Processed Range Resolution (Δr)	0.3 m
Nominal Carrier Frequency (f_o)	1 GHz
Unambiguous Range Window (R_u)	150 m
Fraction of R_u occupied by original range bin ($\tau\Delta F$)	0.1
Range Weighting Function	Hamming (K= 1.33)
Target Range	1208 m
Target Velocity	500 m/s
Target Cross Section	1 m ²
SCR for 1 m ² target	20 dB

1. Effect of Compensation Velocity

The effect of applying velocity compensation factors of 0 m/s (uncompensated), 100 m/s, 300 m/s, 500 m/s, 700 m/s and 1000 m/s for the reference target after applying clutter cancellation is shown in Figures 4.22a-f respectively. In each of these profiles, the effects of noise are assumed to be negligible compared to clutter. All other reference parameters are held constant.

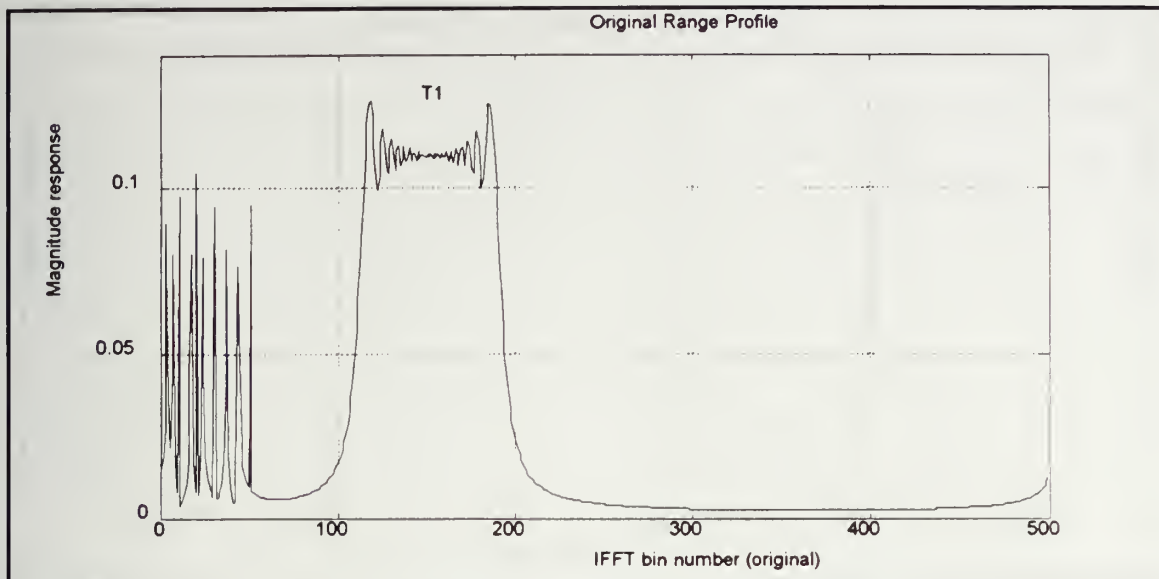


Figure 4.22a Uncompensated HRR Profile. Target velocity = 500 m/s.

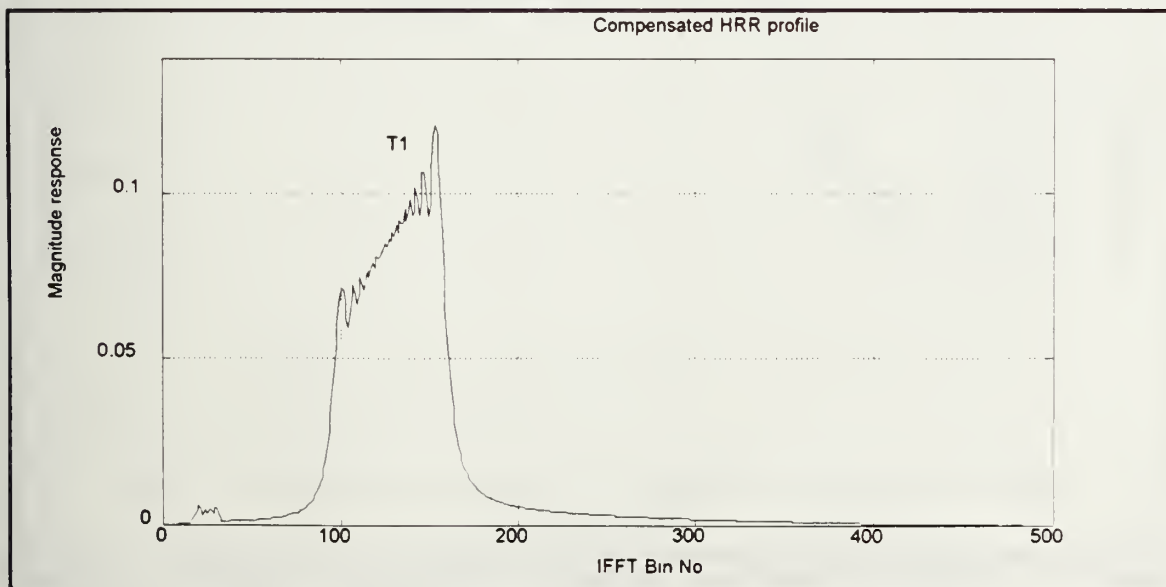


Figure 4.22b HRR Profile with clutter cancellation. Target velocity = 500 m/s.
Compensation velocity = 100 m/s.

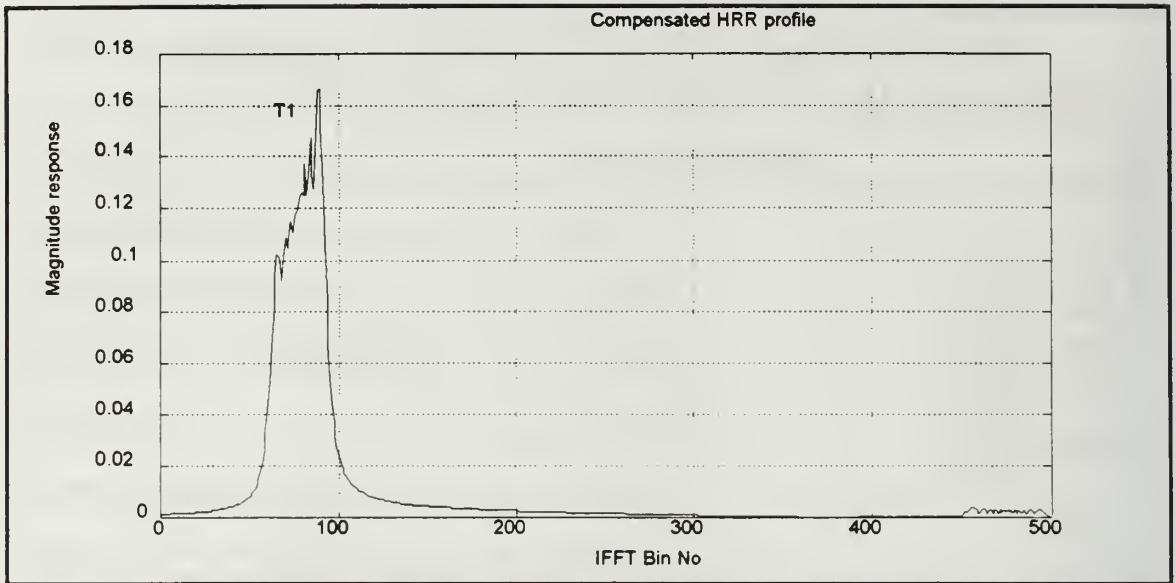


Figure 4.22c HRR Profile with after cancellation. Target velocity = 500 m/s.
Compensation velocity = 300 m/s.

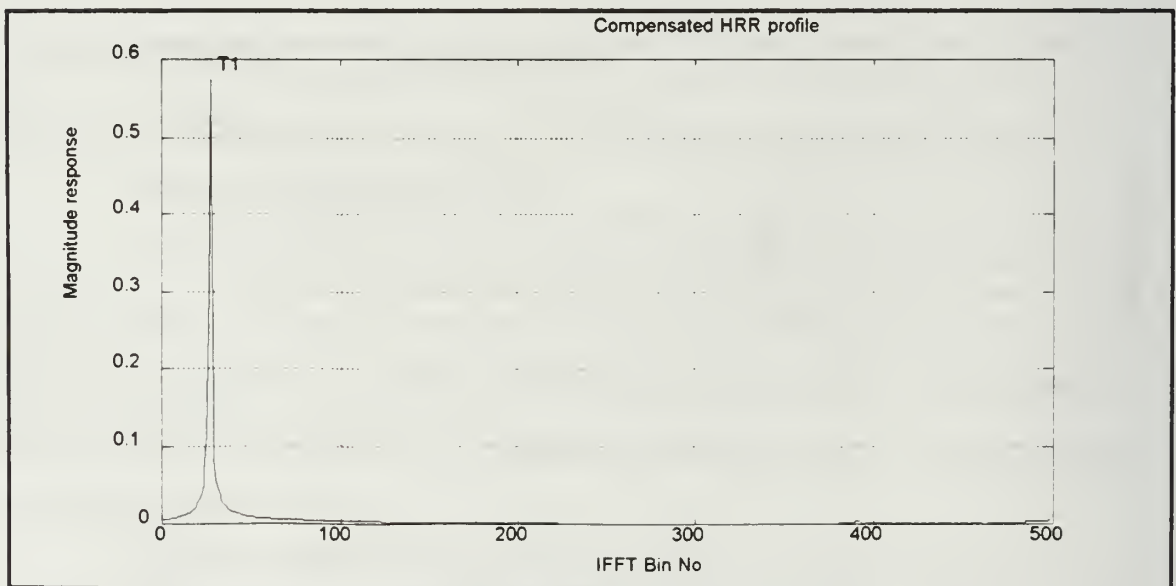


Figure 4.22d HRR Profile with clutter cancellation. Target velocity = 500 m/s.
Compensation velocity = 500 m/s (i.e. correct velocity compensation).
Note the improvement in range resolution for the target peak.

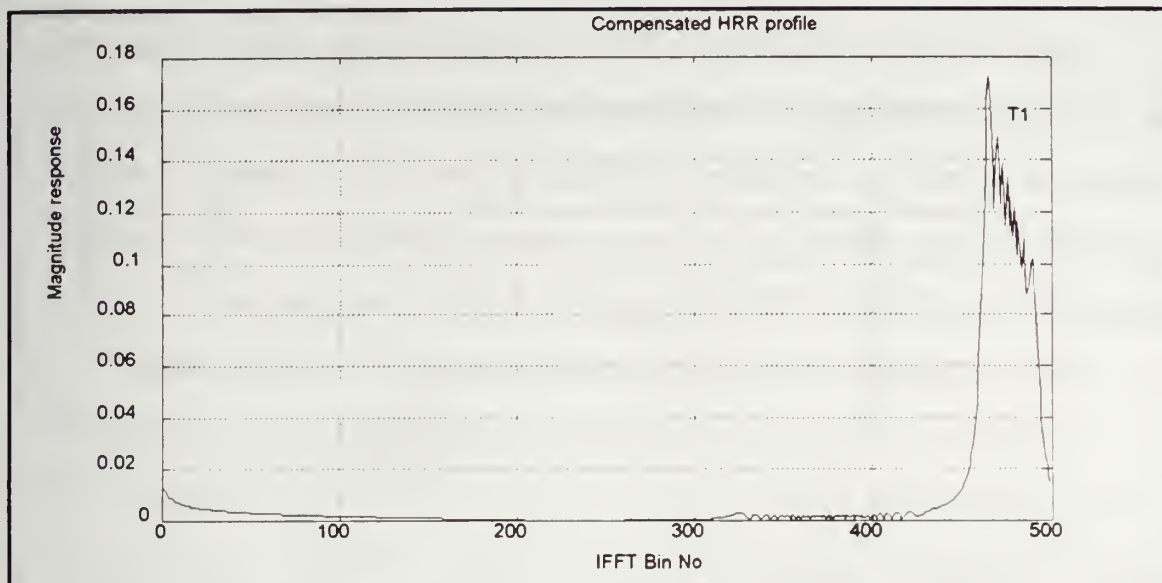


Figure 4.22e HRR Profile with clutter compensation. Target velocity = 500 m/s.
Compensated velocity = 700 m/s.

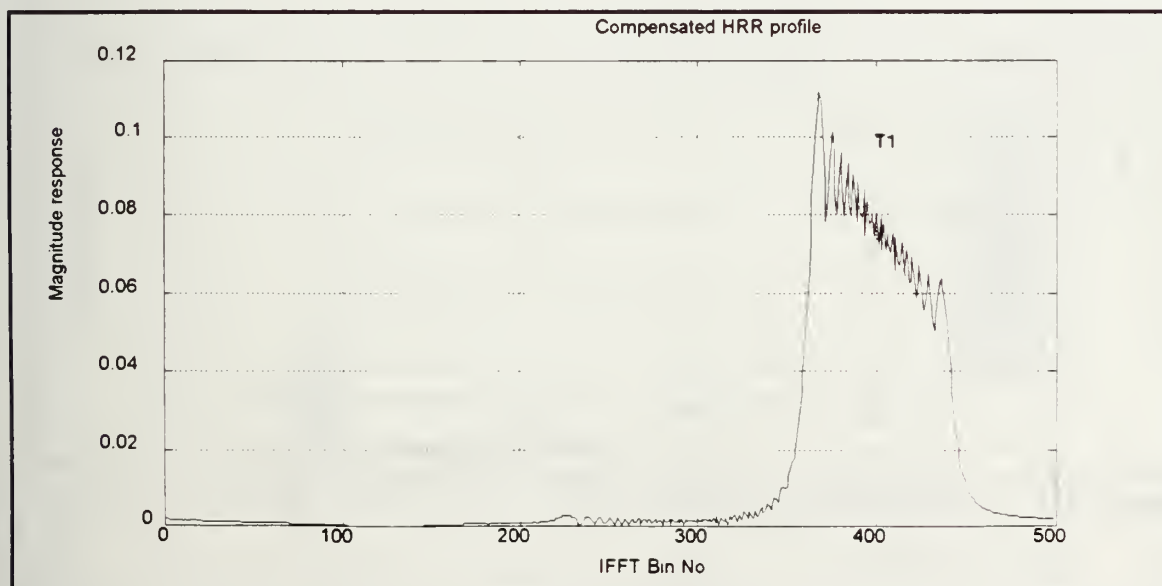


Figure 4.22f HRR Profile with clutter cancellation. Target velocity = 500 m/s.
Compensated velocity = 1000 m/s.

As the velocity compensation factor approaches the true target velocity, the target peak sharpens, resulting in increased signal strength and finer range resolution. This technique will increase the probability of detection as the output is higher for correct compensation. It is also possible to determine the target velocity as the correct velocity compensation gives a larger output as compared with incorrect compensations.

2. Effect of Compensation Velocity at a Reduced Signal to Clutter Ratio

The effects of varying the compensation velocity from 0 m/s to 100 m/s, 300 m/s, 500 m/s, 700 m/s, and 1000 m/s at an SCR of -20 dB are displayed in Figures 4.23a-f respectively. From these figures, it is evident that the signal strength is maximized when the compensation velocity equals the actual target velocity. These HRR profiles follow the same pattern as those with a high SCR of 20 dB which were displayed in Figures 4.22a-f. The major difference is in the relative amplitudes of the target peaks.

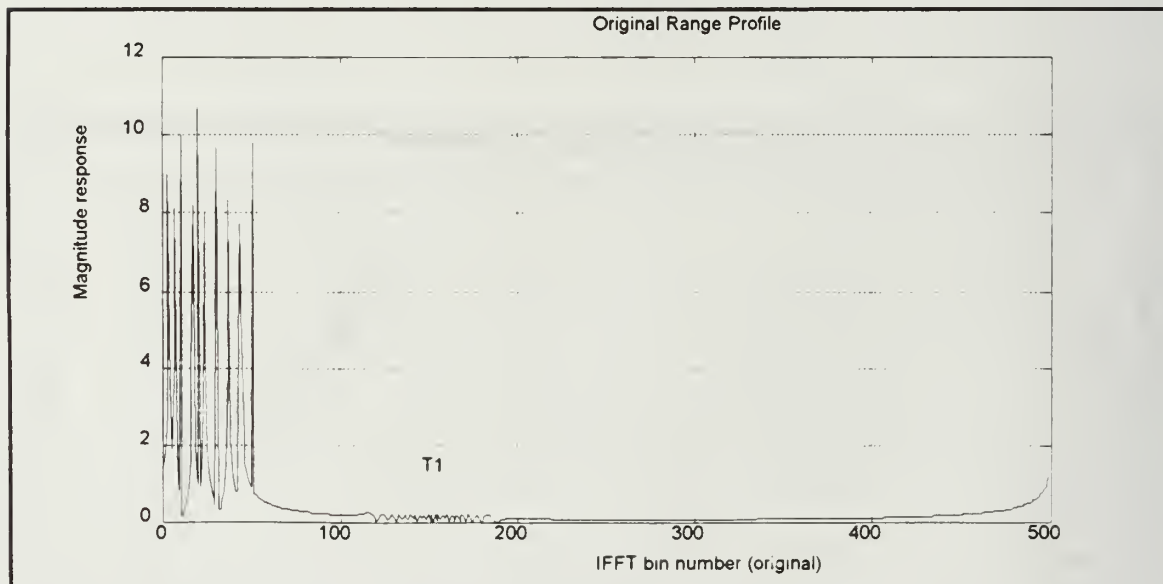


Figure 4.23a Uncompensated HRR Profile. SCR = -20 dB. Target velocity = 500 m/s.

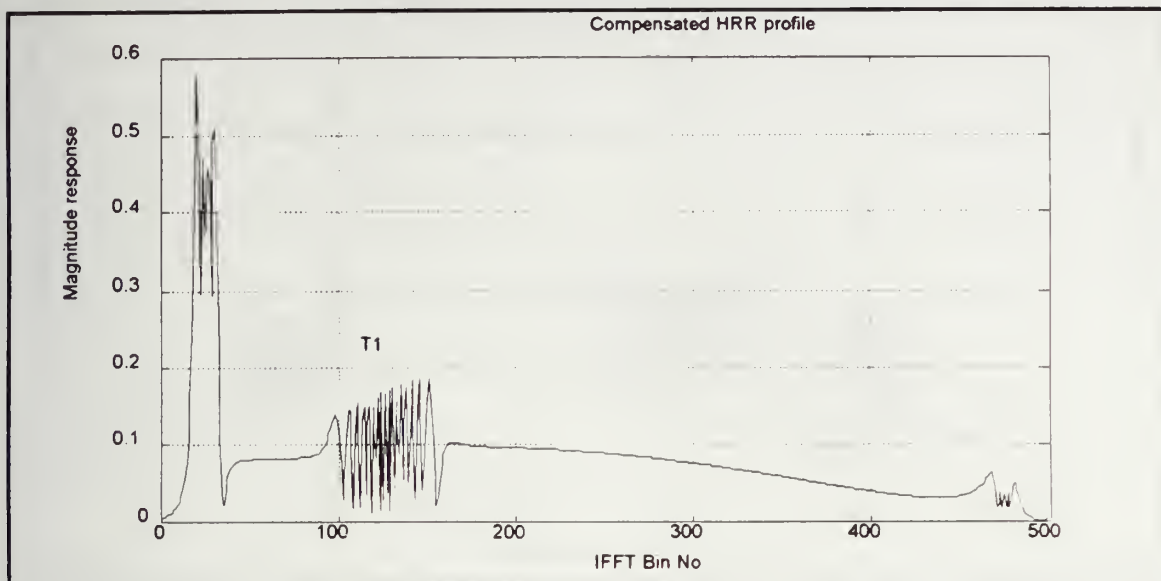


Figure 4.23b HRR Profile with clutter cancellation. SCR = -20 dB.
Target velocity = 500 m/s. Compensated velocity = 100 m/s.

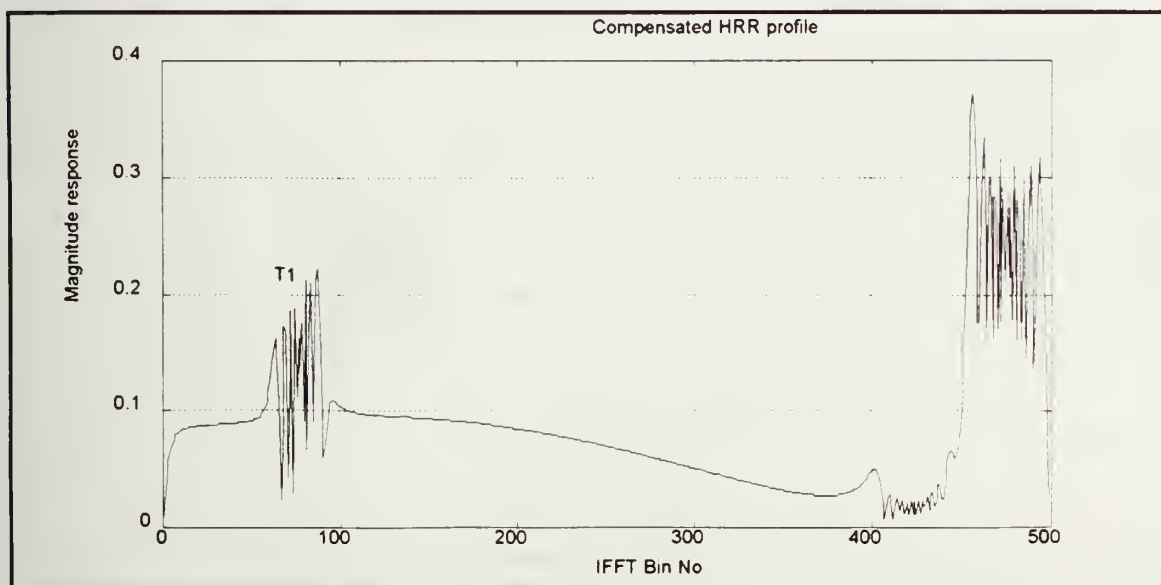


Figure 4.23c HRR Profile with clutter cancellation. SCR = -20 dB.
Target velocity = 500 m/s. Compensated velocity = 300 m/s.

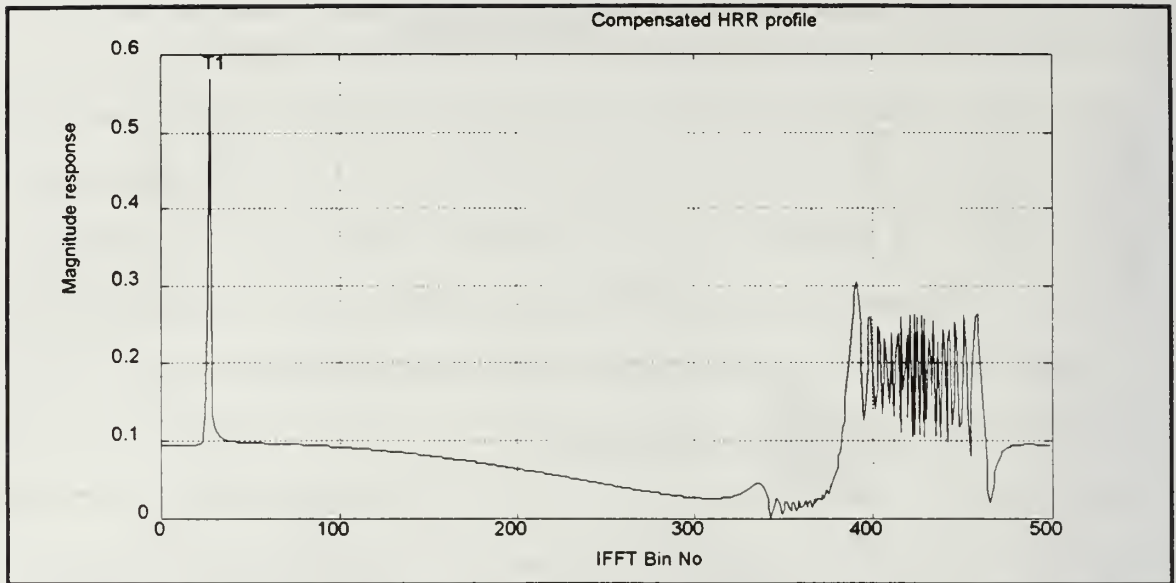


Figure 4.23d HRR Profile with clutter cancellation. SCR = -20 dB.
Target velocity = 500 m/s. Compensated velocity = 500 m/s.

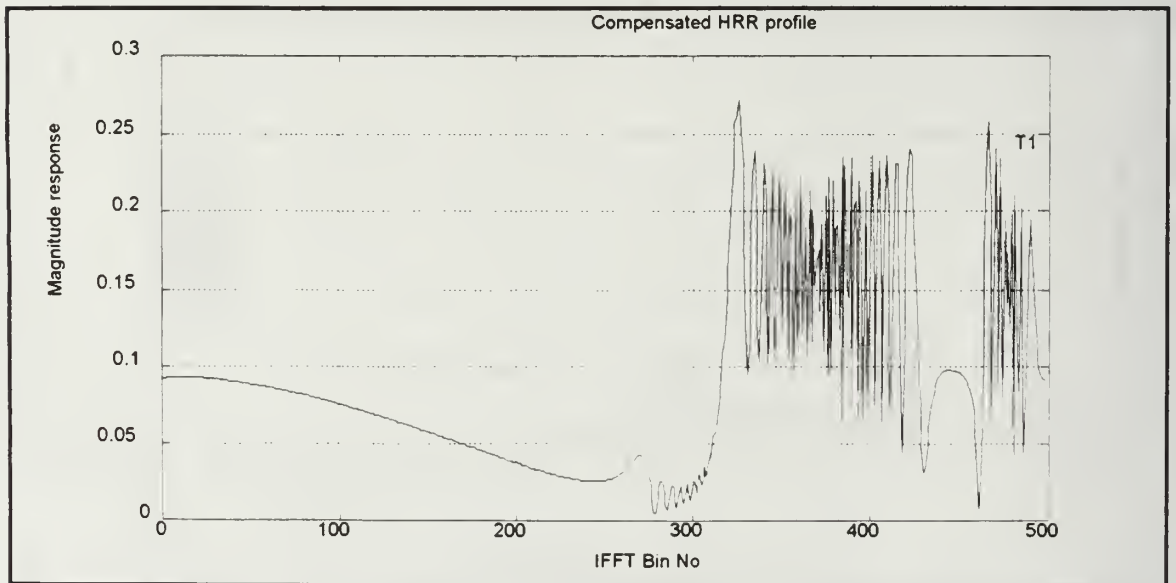


Figure 4.23e HRR Profile with clutter cancellation. SCR = -20 dB.
Target velocity = 500 m/s. Compensation velocity = 700 m/s

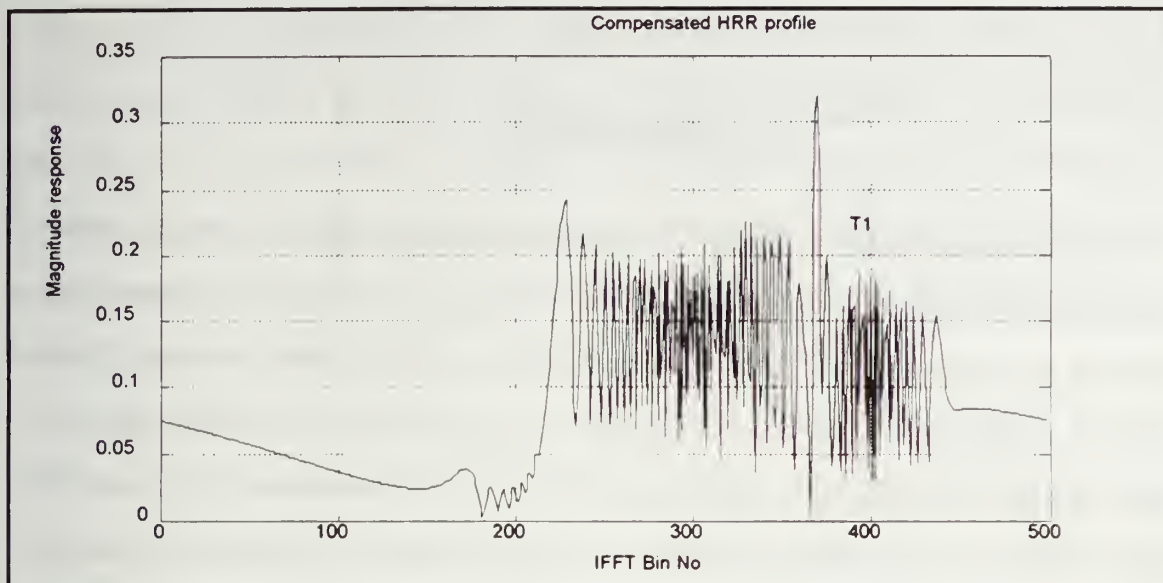


Figure 4.23f HRR Profile with clutter cancellation. SCR = -20 dB.
Target velocity = 500 m/s. Compensation velocity = 1000 m/s.

In summary, a simulation program was developed to display the HRR profile corresponding to a single original range bin of width $c\tau/2$. There are three versions of this program; one for noise limited environments, one for clutter limited environments, and one for clutter limited environments which includes clutter cancellation followed by repeated velocity compensations. The effects of individually varying waveform parameters such as the number of pulses, N , the frequency step size, ΔF , and the PRF on the HRR profile are graphically illustrated, as well as the effects of target motion and velocity compensation.

V. CONCLUSIONS

This thesis investigates the realization of high radar range resolution by means of the step frequency waveform. This waveform achieves high range resolution by coherently processing the returns from N pulses each having a different carrier frequency that changes by a fixed amount, from pulse to pulse. The step frequency waveform has two principal advantages compared to conventional high resolution waveforms. First, since the effective waveform bandwidth is realized over several pulses, each individual pulse is sufficiently wide which eases the A/D sampling requirements. Second, the step frequency waveform can be implemented by conventional radar equipment, with the addition of a stepped frequency synthesizer. Thus high range resolution can be obtained using narrowband components. The primary limitation of the step frequency waveform, as compared to intrapulse pulse compression, is the time required to transmit and receive N pulses needed to obtain the equivalent wide bandwidth of a single narrow pulse.

The effects of various waveform parameters on the high resolution range profile (HRR profile) are determined for both stationary and moving targets in noise and clutter environments. The primary parameters include the number of pulses N , the frequency step size ΔF , the PRF, and the pulse width τ . Design methods are developed based on specified requirements to optimize system performance for a low PRF mode in clutter limited and noise limited situations. The design process specifies the range of values of each of the primary waveform parameters which results in the required system performance.

Target motion in the presence of noise or clutter results in dispersion of the target peak in the HRR profile resulting in lower SNR as well as a shift in the peak location due to range-doppler coupling, which can also result in target wraparound. To overcome these

effects, velocity compensation can be applied to the range profile provided that an accurate target velocity estimate is available. If velocity compensation is not possible, increasing the PRF can mitigate the effects of target motion only for noise limited cases. However, to detect targets in the presence of clutter, target motion is necessary for the peak to migrate into the clutter free region of the profile. For a fixed target velocity, a lower PRF results in further migration into the clutter free zone.

In this thesis, a novel method is proposed to detect moving targets in clutter. Targets shift out of clutter regions due to range-doppler coupling. The resulting shift in range confirms the presence of a target since the clutter free region is free of returns from stationary objects. Velocity compensation can be applied to the HRR profile to determine the true range of an extended target. However, there are two problems to solve. Specifically, the target velocity is unknown, and the portion of the range profile corresponding to the true range is obscured by clutter. These problems are solved as follows. The clutter is canceled by canceling it out once the separation of clutter and target has taken place. Since the target velocity is unknown, compensation can be performed for several different velocities sequentially. The velocity which gives the highest signal magnitude in the compensated profile is the correct target velocity.

Further research efforts in this area should include the study and design of medium and high PRF modes of operation for the step frequency radar. In addition, the properties of the step frequency waveform using the ambiguity function need to be studied. Finally, methods to further refine velocity compensation of moving targets in clutter need to be developed.

APPENDIX A: DESCRIPTION OF HRR SIMULATION PROGRAMS

The purpose of the two simulation programs HRRC.M, and HRRN.M is to recreate a synthetic high range resolution (HRR) profile in clutter limited situations and noise limited situations respectively. HRRCAD.M, the program which simulates clutter cancellation followed by velocity compensation for moving targets in clutter will be discussed later. Each simulation is accessed by the user as a MATLAB function which simulates up to three targets with varying ranges, velocities and cross-sections. In addition to the range profile, the function returns the processed range resolution, and the unambiguous range. The range profile is displayed as a plot of the magnitude response of the inverse FFT in decibels versus the bin number. The following parameters are input by the user in the order shown for both programs:

1. n = the number of coherently integrated pulses
2. f_{step} = the frequency increment between successive pulses (Hz)
3. prf = the pulse repetition frequency of the radar (Hz)
4. r_1 = the initial range to the first target (m)
5. r_2 = the initial range to the second target (m)
6. r_3 = the initial range to the third target (m)
7. v_1 = the radial velocity of the first target (+ = opening) (- = closing) (m/s)
8. v_2 = the radial velocity of the second target " " (m/s)
9. v_3 = the radial velocity of the third target " " (m/s)

In addition to these direct inputs, the following parameters are easily changed within the program. They are as follows:

1. snr = the signal to noise ratio for a 1 m² target (dB)
2. scr = the signal to clutter ratio for a 1 m² target (HRRC.M only) (dB)
3. co = the compensated velocity (+ = opening) (- = closing) (m/s)
4. fo = the carrier frequency (Hz)

The following quantities are computed and presented as outputs:

1. ru = the unambiguous range (m)
2. rstep = the processed range bin size (windowed) (m)

The output parameters can be changed to those more relevant to the user such as the dispersion factor P, and the range bin shift factor L.

Once all parameters are specified, the first step of the program creates the in phase and quadrature samples of the target return signal for the N pulses within the burst. These samples are written in complex exponential form for each target as.

$$s_i(k) = A_i \exp(-j\phi_i(k)) \quad (\text{A.1})$$

where A_i is the amplitude of the return from the kth pulse of the ith target, and ϕ_i represents the corresponding phase. The amplitude of each target return is assumed to remain constant from scan to scan. For a given target, the phase is expressed as follows:

$$\phi(k) = 2\pi f(k)t(k) \quad (\text{A.2})$$

where $f(k)$ is the carrier frequency of the kth pulse, and $t(k)$ is the round trip time for the kth target return. The carrier frequency of the kth pulse within the burst is given by:

$$f(k) = f_o + (k-1)\Delta F \quad (\text{A.3})$$

where ΔF represents the frequency increment between successive pulses. The round trip time of the k th target return is given by:

$$t(k) = \frac{2R(k)}{c} \quad (\text{A.4})$$

where $R(k)$ is the target range for the k th return pulse. The instantaneous target range is specified as:

$$R(k) = R_o + (k - 1)v(\text{PRI}) \quad (\text{A.5})$$

where v is the radial velocity of the target. Substituting the expressions for the target range, the target round trip time, and the carrier frequency into equation (A.2) yields the overall expression for the phase of each return from a given target. Thus the phase $\phi(k)$ is rewritten as:

$$\phi(k) = \frac{4\pi}{c} (f_o + (k - 1)\Delta F)(R_o + (k - 1)v(\text{PRI})) \quad (\text{A.6})$$

A velocity compensation factor is applied to each target return signal to mitigate the effects of the range-doppler coupling caused by the target's radial velocity. The accuracy of the compensation factor depends on specifying the correct target radial velocity. An uncompensated profile is generated by setting the compensation velocity to zero. The simulation uses the same compensation factor for all three targets. Thus, if the three targets have different velocities, none of the targets are compensated exactly. In this case,

the best possible results are obtained by using the average velocity in the compensation factor. The velocity compensation factor is given as:

$$vc(k) = \exp\left(\frac{j4\pi(co)(f_o + (k-1)PRI)}{c}\right) \quad (A.7)$$

where co indicates the compensation velocity.

Thus, with velocity compensation, the k th return signal for a given target becomes

$$s_i(k) = A_i \exp(-j\phi_i(k))vc(k) \quad (A.8)$$

In both simulations, the SNR represents a ratio of the signal power to the noise power as shown below in equation (A.9):

$$SNR = \frac{A^2}{2\sigma^2} \quad (A.9)$$

The reference value of the SNR is set at 0 dB for the 1 m² target (T3) prior to integration and the noise source is modeled as white gaussian noise with a variance of 0.0002. Once the noise variance is set and the SNR is specified for the 1 m² target, the amplitude corresponding to the 1 m² target is determined from equation (A.9). The cross sections of the remaining two targets are specified as 10 m² (T2), and 100 m² (T1) which correspond to target SNR's of 10 dB and 20 dB respectively. Since the target cross sections are proportional to the signal power, increasing the target cross section by a factor of 10 is equivalent to increasing the amplitude A by a factor of $\sqrt{10}$ or 3.16.

In addition to the actual targets, the clutter simulation (HRRC.M) models clutter by including an additional ten closely spaced scatterers within the original range bin of width $c\tau/2$. The range for each clutter source is fixed and the expression for a single clutter source is given as follows:

$$c_i(k) = C \exp\left(\frac{-j4\pi(f_o + (k-1)\Delta F)R_i}{c}\right) \quad (\text{A.10})$$

where C represents the identical magnitude of each clutter source. The value of C is based on the reference value of the signal to clutter ratio (SCR). The signal to clutter ratio, (SCR) represents the ratio of the signal power of a 1 m² target (T3) and a single clutter source. The expression for the SCR is given as:

$$\text{SCR} = \frac{A^2/2}{C^2/2} = \frac{A^2}{C^2} \quad (\text{A.11})$$

where C is the identical clutter magnitude for each clutter source.

The reference value of SCR is set at -20 dB for the 1 m² target. As a result, the signal to clutter ratio for the 10 m² target (T2) and the 100 m² target (T1) are set at -10 dB and 0 dB respectively. The clutter magnitude C is determined based on the amplitude A_3 computed for the 1 m² target (T3) in equation (A.9), and the specified SCR value of -20 dB for that target. The clutter magnitude is given as:

$$C = \sqrt{\frac{(A_3)^2}{(\text{SCR})}} \quad (\text{A.12})$$

The overall return signal for the k th pulse $s(k)$ which consists of the three targets, the noise, and the clutter (if applicable) within one original range bin is given as:

$$s(k) = \sum_{i=1}^3 s_i(k) + \sum_{i=1}^{10} c_i(k) + \sigma n(k) \quad (\text{A.13})$$

where the index i counts the number of targets and clutter sources, k is the pulse index, and $n(k)$ represents the noise source whose standard deviation σ equals $\sqrt{0.0002}$ or 0.04.

Once the set of return signals are generated for one coherent processing interval, the frequency domain data are then multiplied by a weighting function to reduce the sidelobe levels of the inverse FFT. A Hamming window is used which reduces the sidelobes to -43 dB below the main lobe, but also widens the main lobe by 2 dB or a factor of 1.33. As a result, the processed range resolution decreases by the same factor.

The main step in the program computes the Inverse Fourier Transform of the frequency domain samples. The magnitude of the inverse FFT represents the HRR profile. The HRR profile is plotted with the IFFT bin number on the x-axis, and the magnitude of the IFFT in decibels on the y-axis. The final step computes the output quantities such as the unambiguous range and the processed range resolution. In addition, optional output quantities such as the dispersion factor, and the bin shift factor for each target are also determined. The unambiguous range is given by the following relation:

$$R_u = \frac{c}{2\Delta F} \quad (\text{A.14})$$

where ΔF represents the frequency increment between successive pulses. The processed range resolution, is given as:

$$\Delta r = \frac{Kc}{2n\Delta F} \quad (\text{A.15})$$

where K is the factor by which the mainlobe is widened due to windowing ($K = 1.33$ for a Hamming window).

In contrast to the two programs discussed above, HRRCAD.M simulates one moving target in clutter within an original range bin of width $c\tau/2$ and displays the output in terms of magnitude rather than decibels. The magnitude plot is chosen to better illustrate the resulting improvement in the range resolution. The input parameters to this program are entered in the following order:

1. n = the number of coherently integrated pulses
2. f_{step} = the frequency increment between successive pulses (Hz)
3. prf = the pulse repetition frequency of the radar (Hz)
4. scr = the signal to clutter ratio (dB)
5. r = the initial range to the target (m)
6. v = the radial velocity of the target (+ = opening) (- = closing) (m/s)

Once the initial parameters are entered, the program simulates the original clutter limited HRR profile using the same general methods as in HRRC.M. The simulation then prompts the user to enter the highest IFFT bin number which contains clutter, and the compensation velocity for the target. These two parameters are referred to as (bu) and (col) inside the program.

The high bin number, for the clutter region determines the width of the rectangular gating function which cancels the clutter. The gating function multiplies IFFT bin numbers less than or equal to the high bin number with zeros, and the remainder of the original HRR profile with ones to implement the clutter cancellation. To smooth the resulting sidelobes, the original HRR profile is then multiplied by a Hamming window prior to being transformed once again to frequency domain data by the FFT.

Velocity compensation based on the user's estimate is applied to the resulting frequency domain samples. The compensated data are then transformed into the final HRR profile by the inverse FFT. The resulting profile is free of clutter, and indicates an increase in the target's signal strength provided that the correct compensation velocity has been entered. In addition, the program returns the unambiguous range R_u and the processed range resolution Δr .

APPENDIX B: HRR SIMULATION PROGRAM CODES

```

*****
function [ru,rstep] = hrrn(n,fstep,prf,r1,r2,r3,v1,v2,v3)
% This program is a MATLAB function which computes the HRR profile of
% a single range bin in noise limited situations.
% The following data are inputs for each of the 3 targets:
%     Number of pulses (n)
%     Frequency step size (fstep)
%     Pulse Repetition Frequency (prf)
%     Initial Target Ranges (r1, r2, r3)
%     Target Radial Velocity (v1, v2, v3)(+ opening)(- closing)

% The following parameters can be changed within the function
%     Signal to Noise Ratio in (dB) for each target (snr)
%     Nominal carrier frequency (fo)
%     Velocity matched for compensation (co)
% The outputs are Ru = c/2*fstep, and Rstep = Kc/2*n*fstep,
% which are the unambiguous range and processed range bin size.
% The FFT size is equal to n.
% The frequency domain data are weighted by a Hamming window. (K=1.33)
% The noise is white gaussian noise with zero mean and variance equal to .0002.

% Initialize parameters
co = 0;
fo = 1e9;
snr = 0;
x=[0:n-1];
c = 3e8;
K = 1.33;
PRI = 1/prf;

% Convert the SNR from decibels to magnitude
a = 10 ^ (snr/10);
A3 = sqrt(2*a*.0002);
A2 = sqrt(10)*A3;
A1 = sqrt(100)*A3;

% Generate the frequency domain data
for k=1:n,
    f(k) = fo + (k-1)*fstep;
    vc(k) = exp(j*4*pi*co*f(k)*(k-1)*PRI/c);
    s1(k) = A1*exp(-(4*pi/c)*f(k)*(r1 +(k-1)*v1*PRI))*vc(k);
    s2(k) = A2*exp(-(4*pi/c)*f(k)*(r2 +(k-1)*v2*PRI))*vc(k);
    s3(k) = A3*exp(-(4*pi/c)*f(k)*(r3 +(k-1)*v3*PRI))*vc(k);
    s(k) = (s1(k)+s2(k)+s3(k)) + sqrt(.0002)*randn;
end

```

```
% Compute the IFFT
```

```
h = hamming(n);
```

```
sw = s .* h';
```

```
S = ifft(sw);
```

```
mag = abs(S);
```

```
dbmag = 20*log10(mag);
```

```
% Compute output quantities
```

```
ru = c/(2*fstep);
```

```
rstep = (K*c)/(2*n*fstep);
```

```
P = v1*n*PRI/rstep; range resolution due to radial vel (if range bin
```

```
B = n*fstep; range of doppler freq
```

```
fc = fo + B/2;
```

```
L = (fc/B)*P; range bin shift
```

```
% Plot the HRR Profile
```

```
plot(x,dbmag)
```

```
grid
```

```
xlabel('IFFT bin number ')
```

```
ylabel('Magnitude response in dB')
```

```
gtext('T1')
```

```
gtext('T2')
```

```
gtext('T3')
```

```
*****
```

```
function [ru,rstep] = hrrc(n,fstep,prf,r1,r2,r3,v1,v2,v3)
% This program is a MATLAB function which
% computes the HRR profile in clutter limited situations
% The following data are inputs for each of the 3 targets:
%      Number of pulses (n)
%      Frequency step size (fstep)
%      Pulse Repetition Frequency (prf)
%      Initial Ranges (r1, r2, r3)
%      Target Radial Velocity (v1, v2, v3)(+ opening)(- closing)
% The following parameters can be changed within the function
%      Nominal carrier frequency (fo)
%      Signal to Noise Ratio in (dB) for each target (snr)
%      Signal to Clutter Ratio in (dB) for each target (scr)
%      Compensated velocity (co)

% The outputs are Ru = c/2*fstep, and Rstep = Kc/2*n*fstep,
% which are the unambiguous range and processed range bin size.
% The frequency domain data are weighted by a Hamming window. (K = 1.33)
% The noise is white gaussian noise with zero mean and unit variance.
```

```
% Initialize parameters
```

```
fo = 1e9;
snr = 0;
scr = -20;
co = 0;
K = 1.33;
c = 3e8;
x = [0:n-1];
a = 10^(snr/10);
A3 = sqrt(2*a*.0002);
A2 = sqrt(10)*A3;
A1 = sqrt(100)*A3;
b = 10^(scr/10);
C = sqrt((A3^2)/(b));
```

```
% Generate the frequency domain data
```

```
for k=1:n,
    f(k) = fo + (k-1)*fstep;
    vc(k) = exp(j*4*pi*co*f(k)*(k-1)*PRI/c);
    s1(k) = A1*exp(-(j*4*pi/c)*f(k)*(r1 + (k-1)*v1*PRI))*vc(k);
    s2(k) = A2*exp(-(j*4*pi/c)*f(k)*(r2 + (k-1)*v2*PRI))*vc(k);
    s3(k) = A3*exp(-(j*4*pi/c)*f(k)*(r3 + (k-1)*v3*PRI))*vc(k);
    c1(k) = C*exp(-(j*4*pi/c)*f(k)*1);
    c2(k) = C*exp(-(j*4*pi/c)*f(k)*2);
    c3(k) = C*exp(-(j*4*pi/c)*f(k)*3);
    c4(k) = C*exp(-(j*4*pi/c)*f(k)*5);
    c5(k) = C*exp(-(j*4*pi/c)*f(k)*6);
    c6(k) = C*exp(-(j*4*pi/c)*f(k)*7);
    c7(k) = C*exp(-(j*4*pi/c)*f(k)*9);
    c8(k) = C*exp(-(j*4*pi/c)*f(k)*11);
    c9(k) = C*exp(-(j*4*pi/c)*f(k)*13);
    c10(k) = C*exp(-(j*4*pi/c)*f(k)*15);
```



```

s(k) = (s1(k)+s2(k)+s3(k)) + (c1(k)+c2(k)+c3(k)+c4(k)+c5(k)+c6(k) ...
      + c7(k)+c8(k)+c9(k)+c10(k)) + sqrt(.0002)*randn;

end

% Compute the IFFT
h = hamming(n);
sw = s .* h';
mag = abs(S);
dbmag = 20*log10(mag);

% Compute the output quantities
ru = c/(2*fstep);
rstep = K*c/(2*n*fstep);
p1 = v1*n*PRI/rstep;
p2 = v2*n*PRI/rstep;
p3 = v3*n*PRI/rstep;
P = [p1 p2 p3];
B = n*fstep;
fc = fo + B/2;
L = (fc/B) .* P;

% Plot the HRR Profile
plot(x,dbmag)
grid
xlabel('IFFT bin number ')
ylabel('Magnitude response in dB')
gtext('T1')
gtext('T2')
gtext('T3')
*****

```

```
function [ru,rstep] = hrrcad(n,fstep,prf,scr,r,v)
% This program is a MATLAB function which computes
% the HRR profile of a single moving target in clutter.
% This program includes clutter cancellation
% followed by velocity compensation.
% The input data consists of the following:
%     Number of pulses (n)
%     Frequency step size (fstep)
%     Pulse Repetition Frequency (prf)
%     Signal to Clutter Ratio for 1 square meter target (scr)
%     Initial Target Range (r)
%     Target Radial Velocity (v) (+ opening) (- closing)
% The following parameters can be changed within the function
%     Amplitude of return signal for 1 square meter target (A1)
%     Nominal carrier frequency (fo)
% The following parameters are input by the user after the
% original HRR profile is displayed:
%     Highest IFFT bin containing clutter (bu)
%     Compensation velocity (co1)
% The outputs are Ru = c/2*fstep, and Rstep = K*c/2*n*fstep,
% which are the unambiguous range and processed range bin size.
% The FFT size is equal to n.
```

```
% initialize parameters
fo = 1e9;
x=[0:n-1];
c = 3e8;
PRI = 1/prf;
A1 = 1;
b = 10^(scr/10);
% B is the clutter magnitude
B = sqrt((A1^2)/b);
```

```
for k=1:n,
    f(k) = fo + (k-1)*fstep;
    s1(k) = A1*exp(-(j*4*pi/c)*f(k)*(r1 + (k-1)*v1*PRI));
    c1(k) = B*exp(-(j*4*pi/c)*f(k)*1);
    c2(k) = B*exp(-(j*4*pi/c)*f(k)*2);
    c3(k) = B*exp(-(j*4*pi/c)*f(k)*3);
    c4(k) = B*exp(-(j*4*pi/c)*f(k)*5);
    c5(k) = B*exp(-(j*4*pi/c)*f(k)*6);
    c6(k) = B*exp(-(j*4*pi/c)*f(k)*7);
    c7(k) = B*exp(-(j*4*pi/c)*f(k)*9);
    c8(k) = B*exp(-(j*4*pi/c)*f(k)*11);
    c9(k) = B*exp(-(j*4*pi/c)*f(k)*13);
    c10(k) = B*exp(-(j*4*pi/c)*f(k)*15);
    s(k) = s1(k) + (c1(k)+c2(k)+c3(k)+c4(k)+c5(k)+c6(k)...
        +c7(k)+c8(k)+c9(k)+c10(k));
```

```
end
```

```

% Compute original range profile
% Determine output quantities, Ru and rstep
S = ifft(s);
mag = abs(S);
ru = c/(2*fstep);
rstep = K*c/(2*n*fstep);
plot(x,mag)
grid
title('Original Range Profile')
xlabel('IFFT bin number (original) ')
ylabel('Magnitude response ')
gtext('T1')

```

```

% Obtain user input for clutter cancellation and
% compensation velocity
bu = input('Enter high bin number for clutter ')
co1 = input('Enter velocity for target 1')
ss1 = [zeros(1:bu) ones(1:n-bu)] .* S;

```

*to
simplified model*

```

% Window the range domain data
h = hamming(n);
ss1 = ss1 .* h';

```

```

for k=1:n,
    f(k) = fo + (k-1)*fstep;
    vc1(k) = exp(j*4*pi*co1*f(k)*(k-1)*PRI/c);
end

```

```

% Apply velocity compensation to transformed data
SS1 = fft(ss1) .* vc1;

```

```

% Compute final range profile
FSS = ifft(SS1);
finplot = (abs(FSS));
figure
plot(x,finplot);
title('Compensated HRR profile')
xlabel('IFFT Bin No')
ylabel('Magnitude response')
grid
gtext('T1')

```

```

*****

```

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